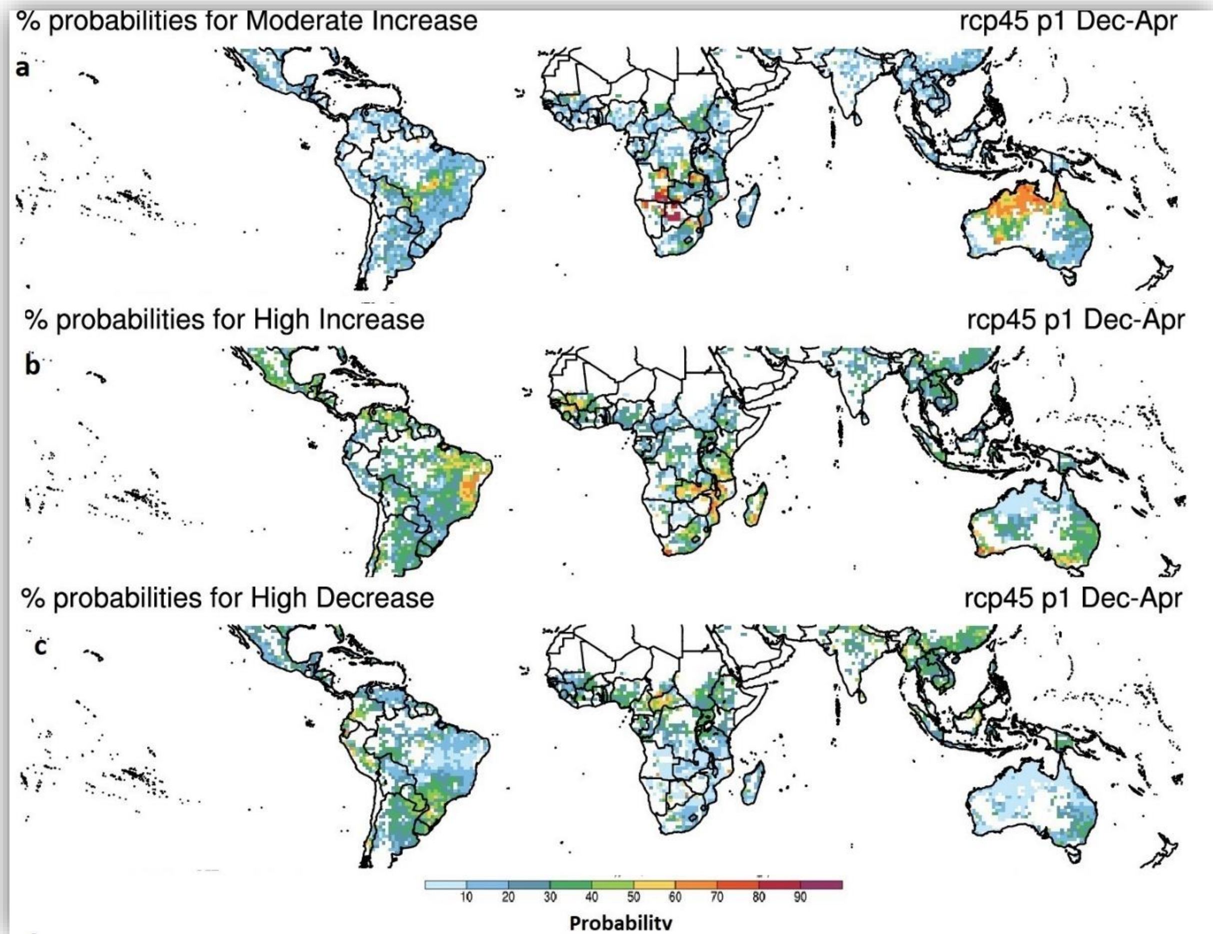
Identifying future hotspots of fire danger in the tropics: climate fire predictions for 2050, 2075 and 2100

Rosa Maria Roman-Cuesta[1], Gil Lizano[2]

1. Center for International Forestry Research (CIFOR) Jl. Raya Cifor, Bogor, Jawa Barat 16115, Indonesia. r.roman-cuesta@cgiar.org
2. VORTEX. Vortex SL Parc Tecnologic Barcelona. Carrer Marie Curie 8-14. 08042 Barcelona. Spain



Executive summary

Recent bursts in the incidence of large wildfires worldwide have raised concerns about the influence that climate and humans may have on future fire activity. Climate strongly influences global wildfire activity, and recent wildfire surges may signal fire weather-induced pyrogeographic shifts. Fire weather seasons have lengthened across ca.3 0 million km2 (25 % of the Earth's vegetated surface), resulting in an 19% increase in global mean fire weather season length, which would allow for a doubling of the global burnable area affected *if* these fire weather changes were coupled with ignition sources and available fuel, which are largely controlled by humans.

Disagreement exists on the relative importance of climate versus human drivers in shaping global fire regimes, with a particular gap in the pantropical region where fire has had a long presence in savannas, montane grasslands and dry forest ecosystems, but it has had a much more recent, infrequent and unknown role in many moist forest ecosystems such as rainforests and cloud montane forests. Either climate or human induced, scenarios of future increases in burned area (fire danger) are needed to i) navigate fire danger reduction policies (e.g fire management that controls prevention, suppression and restoration), ii) to understand how to improve fire-resilient landscapes, iii) to reduce Greenhouse Gas emissions from fire, particularly in regions with carbon-dense fires, and iv) to support capacity building for effective fire management development and implementation.

In this research we map pantropical future fire danger in 2050 (2025-2049), 2075 (2050-2074), 2100 (2075-2099). Fire danger is here understood as the probability of fire spreading over more extended areas under severe climatic conditions (precipitation, temperature and drought), under more extreme future conditions determined by the CMIP5 data. Because human decisions on the land are difficult to model and project in the future, we here focus on projecting climate-driven fire danger only.

Fire danger projections

The projections for Fire danger followed those of precipitation with higher agreement in increasing burned areas than in decreasing for the near future. Increased fire danger strongly focused on **tropical dry ecosystems** (forests and woodlands) with moderate increases projected for the Southern African (Zambia, Angola, Botswana) Miombo and woodlands, northern Australian woodlands and savannahs, and central-eastern dry Cerrado forests in Brazil (all of them with 70-90% of agreement). High increases in fire danger also focused on dry forests and mainly affected the dry Cerrado forests in Eastern Brazil and the Miombo forests of Eastern-Southern Africa (all of them with 70-90% of agreement).

Burned area projections (moderate increase) closely matched currently observed trends of increasing burned areas in Southern Africa (miombo) (Andela et al. 2017), agreed with the importance of fire in Brazilian Cerrado, although more to the west that currently observed, but disagreed with the observed decreasing trends in Northern Australian (woodlands and shrubs). Contrarily, our fire danger projections highly agree on moderate increase of burned area in Northern Australia for ca. 2050, with no decreasing trend.

Precipitation-induced variation and trends

Precipitation projections led fire danger in two directions: Negative correlations between precipitation and burned areas (decrease in burned area with increased precipitation) were observed in forested and wet grassland areas (e.g. Peru, Southern Brazil-Uruguay, Northern Argentina, South Eastern Asia and China), while positive correlations (increased burned area with increased precipitation) affected low fuel xeric ecosystems (e.g. Sub-Saharan Africa). Thus, high levels of precipitation prior to the onset of the fire season may increase fire activity in arid regions because greater moisture availability enhances herbaceous biomass production and thus fuel build-up and continuity, whereas higher levels of precipitation during the fire season may suppress fires because of increases in fuel moisture. Both effects can occur within the same region, with their relative importance depending on the timing and magnitude of precipitation anomalies.

Comparison with other Fire projections

Our fire danger predictions matched surprisingly well the very differently produced scenarios of future fire activity by Pechony and Shindell (2010) who used the GISS GCM model and three IPCC development scenarios (A2, A1B, B1): from a more aggressive development and population growth scenario (A1) to more environmental and reduced human pressure scenario (B1). Particularly close to scenario A1, our fire danger projections agreed with a decrease of Sub-Saharan fire activity, as well as less fire in Western South America (Peru), Southern Brazil-Uruguay and Northern Argentina. Similarly, our projected fire danger agreed with an increase of fire activity in Southern and Eastern Southern Africa, increases in Australia (generalized increase in the GISS model), and increases in western Brazil (border Bolivia-Brazil), Eastern-Brazil, and Venezuela.

Burned Area **RCP4.5, 2025-2049, Dec-April dry season** **Most changes in intervals:** • **High Decrease** • **Moderate Increase** • **High Increase**	High Decrease Sub-Saharan Africa (40-60%) Moderate Increase Central Southern Africa (Zambia, Angola, Botswana) (70-90%) High Increase Eastern Southern Africa (70-80%)	High Decrease Southern Brazil, central Peru (40-60%) Uruguay, Northern Argentina (30-40%) Moderate Increase Central Brazil, Northern Bolivia (50-60%) High Increase Eastern Brazil (50-70%), Venezuela (50%)	High Decrease Western Myanmar (50-70%) Southern China, Viet Nam, south Eastern Australia Moderate Increase Northern Australia (70-90%) High Increase South-western Australia (50-70%), parts of central-eastern Australia (50%)	Consistency between RCP4,5 and 8.5 with fading probabilities along time Higher probabilities for projected changes in Dec-April dry season fires Probabilities of increase are higher than probability of decrease Different spatial locations for fire danger probabilities for Dec-Apr than for May-Nov

Table 1: summary of Temperature, Precipitation and Burned area projections focusing on the highest probabilities: RCP4.5, season Dec-April, and time period 2025-2049)

Highlights

- Currently observed (1998-2015) and projected (2025-2049) hotspots of fire activity (burned area) all agree on a disproportional pressure over dry ecosystems, (Miombo, Cerrado, woodlands, shrublands) which will most likely have consequences for land desertification, water security and human migration.

- There is generally good agreement between currently observed trends of burned area (1998-2015) and projected hotspots of fire danger in Africa (same geographical region) and America (same ecosystem) but full disagreement on the trend of northern Australian Savannahs which our projections agree on increased fire danger while current trends show a clear decrease.

- While precipitation is an undisputed key driver of global fire, land activities and population dynamics also influence fire trends (particularly when climate is moderate). Next steps should investigate how human and economic development could be modelled to predict future fire activity and hotspots of fire danger.

Background

Recent bursts in the incidence of large wildfires worldwide have raised concerns about the influence that climate and humans may have on future fire activity. Climate strongly influences global wildfire activity, and recent wildfire surges may signal fire weather-induced pyrogeographic shifts (Jolly et al. 2015) These authors' showed how fire weather seasons have lengthened across ca.3 0 million km2 (25 % of the Earth's vegetated surface), resulting in an 19% increase in global mean fire weather season length, which would allow for a doubling of the global burnable area affected *if* these fire weather changes were coupled with ignition sources and available fuel, which are largely controlled by humans.

Disagreement exists on the relative importance of climate versus human drivers in shaping global fire regimes, with a particular gap in the pantropical region where fire has had a long presence in savannas, montane grasslands and dry forest ecosystems, but it has had a much more recent, infrequent and unknown role in many moist forest ecosystems such as rainforests and cloud montane forests. In line with this debate, the 2019 fire season, with its global fire emergencies in boreal, temperate and tropical ecosystems, show-cases how global fire trends simultaneously respond to large-scale climate pressures. However, 2019 also showed-cased -once again- how fire effectively trespasses non-adapted wet ecosystems such as the Amazonian lowland rainforests (Brazil, Peru, Bolivia, Colombia), or the swamp peats of Indonesia, when human actions have led to ecosystem degradation and turned them vulnerable to fire.

Recent global fire modelling on the effects of climate, land cover and population growth suggests consecutive and marked shifts of global fire regimes along time (Pechony and Shindell 2010): from a strongly precipitation-driven regime in pre-Industrial times, to a human-driven global fire regime after the Industrial revolution (through fire suppression), and to future projections suggesting an impending shift to a temperature-driven global fire regime. If these modelling results are correct, and temperature rather than precipitation leads fire trends, the 21st century will create an unprecedentedly fire-prone environment outweighing direct human influences on fire (both ignition and suppression). These trends will have dire and imminent effects on fire management policies which will have to adapt to a world where climate, through temperature mediated fuel desiccation, drives global fire regimes.

The relative importance of human vs climate drivers and the ecological consequences of fire will vary among regions, selected time periods (i.e baselines), and ecosystems' fire resilience. As an example, recent fire trends (1998-2015) show how areas with rapid population growth like China and India have seen an increase in fire due to agricultural intensification and increased crop residue burning, while other areas like Africa have seen a decline due to rainfall-increases in vegetation productivity in Northern Africa, and commercial agricultural expansion and intensification in central and western Africa (Andela et al. 2017).

Either climate or human induced, scenarios of future increases in burned area (fire danger) are needed to i) navigate fire danger reduction policies (e.g fire management that controls prevention, suppression and restoration), ii) to understand how to improve fire-resilient landscapes, iii) to reduce Greenhouse Gas emissions from fire, particularly in regions with carbon-dense fires, and iv) to support capacity building for effective fire management development and implementation.

In this research we aim to map pantropical future fire danger in 2050 (2025-2049), 2075 (2050-2074), 2100 (2075-2099). Fire danger is here understood as the probability of fire spreading over more extended areas under severe climatic conditions (precipitation, temperature and drought). Because human decisions on the land are difficult to model and project in the future, we here focus on projecting climate-driven fire danger only.

Methods

We worked pantropically (28N-38S), at 0.5 degrees of spatial resolution (ca.50km), for all ecosystems along the selected latitude belt.

Fire data relied on MODIS MCD64 monthly burned area at 500m of spatial resolution downloaded from the Global Fire Atlas at https://glihtdata.gsfc.nasa.gov/files/fire_atlas which only covered the period 2003-2016. For climate data we used CRU Gridded Data at 0.5 degrees, monthly resolution for the period 1979-2017 downloaded from the University of East Anglia for the variables temperature, precipitation and drought (scPDSI) (https://crudata.uea.ac.uk/cru/data/hrg/). 2003-2016 was the time period used to fit the linear responses of climate-fire. 1981-2005 was selected as the historical period to contrast against future climate conditions. We used the CMIP5 Model Dataset (https://esgf-node.llnl.gov/projects/cmip5/) to estimate future climate conditions in 2050, 2075 and 2100. The CMIP5 is a compendium of ~40 models for several GHG concentration and development scenarios known as Representative Concentration Pathways (RCPs)[1], that cover precipitation and mean temperature changes for the period 2005-2099. We chose two RCPS: a conservative pathway that complies with a radiative forcing in line with the UNFCCC 2 degree C target (RCP4.5), and a liberal pathway (RCP8.5) with much higher GHG concentrations.

To understand the reactivity of burned area to future climate conditions we followed a 2-step process:

1. Search for empirical evidence of linear responses between burned area and climate variables (precipitation, temperature, drought) in the tropics.

2. Produce future projections of climate-driven fire using CMIP5 climate data in 2050, 2075 and 2100 considering past empirical evidence.

The analysis of empirical fire-climate responses considered only a linear fit between MODIS burned area and CRU anomalies for: ○ Precipitation only ○ Precipitation and temperature. This linear fit was done per pixel, at 0.5 degrees, pantropically, for the years 2003-2016 due to MODIS temporal availability. Linear models were fitted for two seasons: ○ Dec-April ○ May-November as the two most plausible dry-seasons in the tropic (Figures 1 and 2). Linear models helped us assess the percentage of burned area driven by a threshold of precipitation decrease or temperature increase. We used these linear models to project changes in burned area related to projected changes in precipitation or temperature by the CMIP5 data in 2050 (2025-2049), 2075 (2050-2074) and 2100 (2075-2099). We compare the projected precipitation and temperature changes in the future with the 1981-2005 historical period means, and computed change statistics that are applied to estimate changes in burned area. Change statistics for the climate variables are shown as probabilities for different ranges of change (number of models predicting change in each of the intervals of climate change). Predicted changes in burned area are shown as probabilities for burned area increases/decreases (number of models predicting change in each of the burned area responses).

Responses between projected climate under the CMIP5 models and burned area were only significant for precipitation. The short period under analysis (2003-2016), the existing background of increasing temperature trend, and the high scale for spatial resolution (0.5 degrees) may have confounded temperature-burned area interactions. For this reason, only precipitation was used to project future fire danger (increases burned area trends) in the tropics.

---

[1] https://en.wikipedia.org/wiki/Representative_Concentration_Pathway; https://ar5-syr.ipcc.ch/topic_futurechanges.php

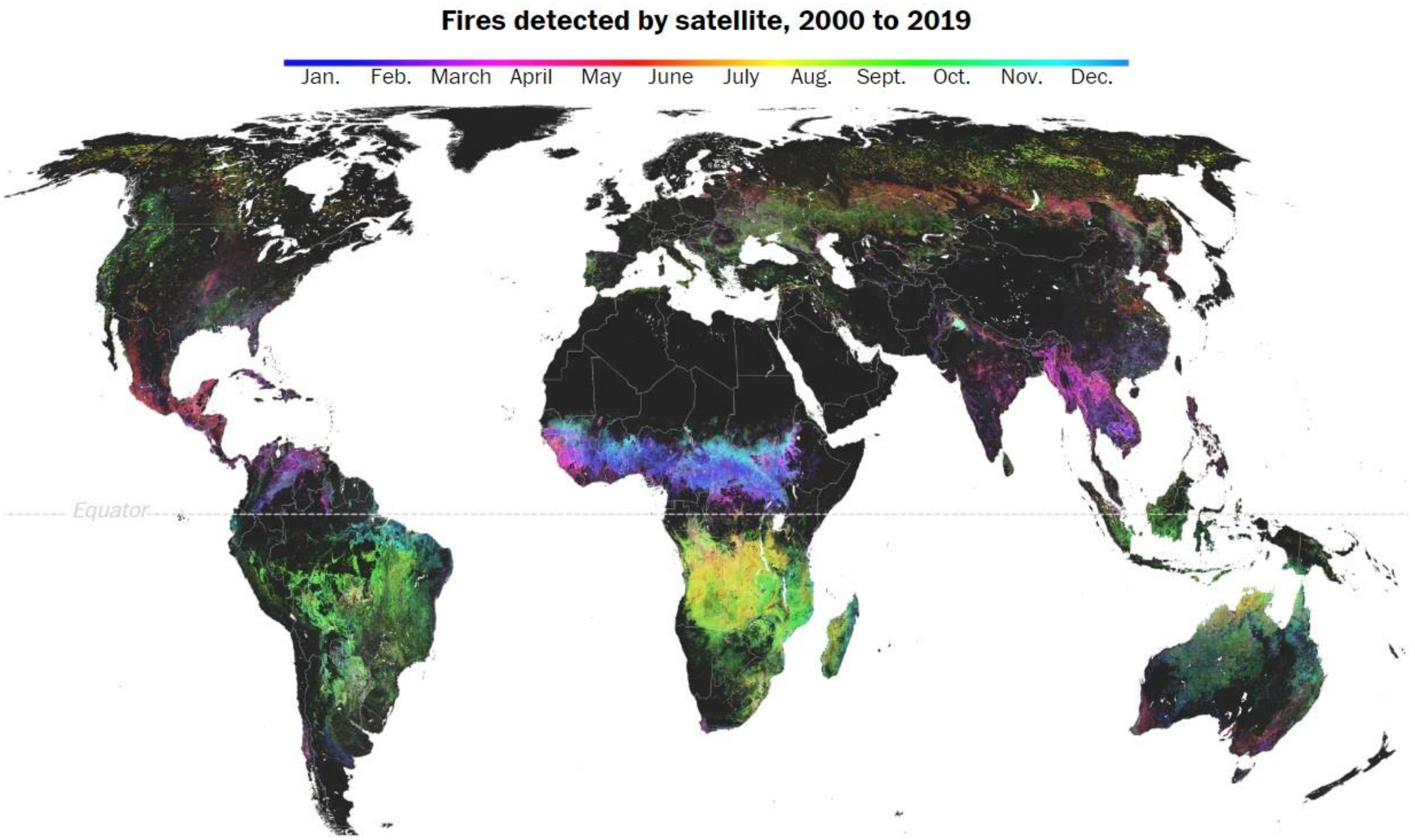
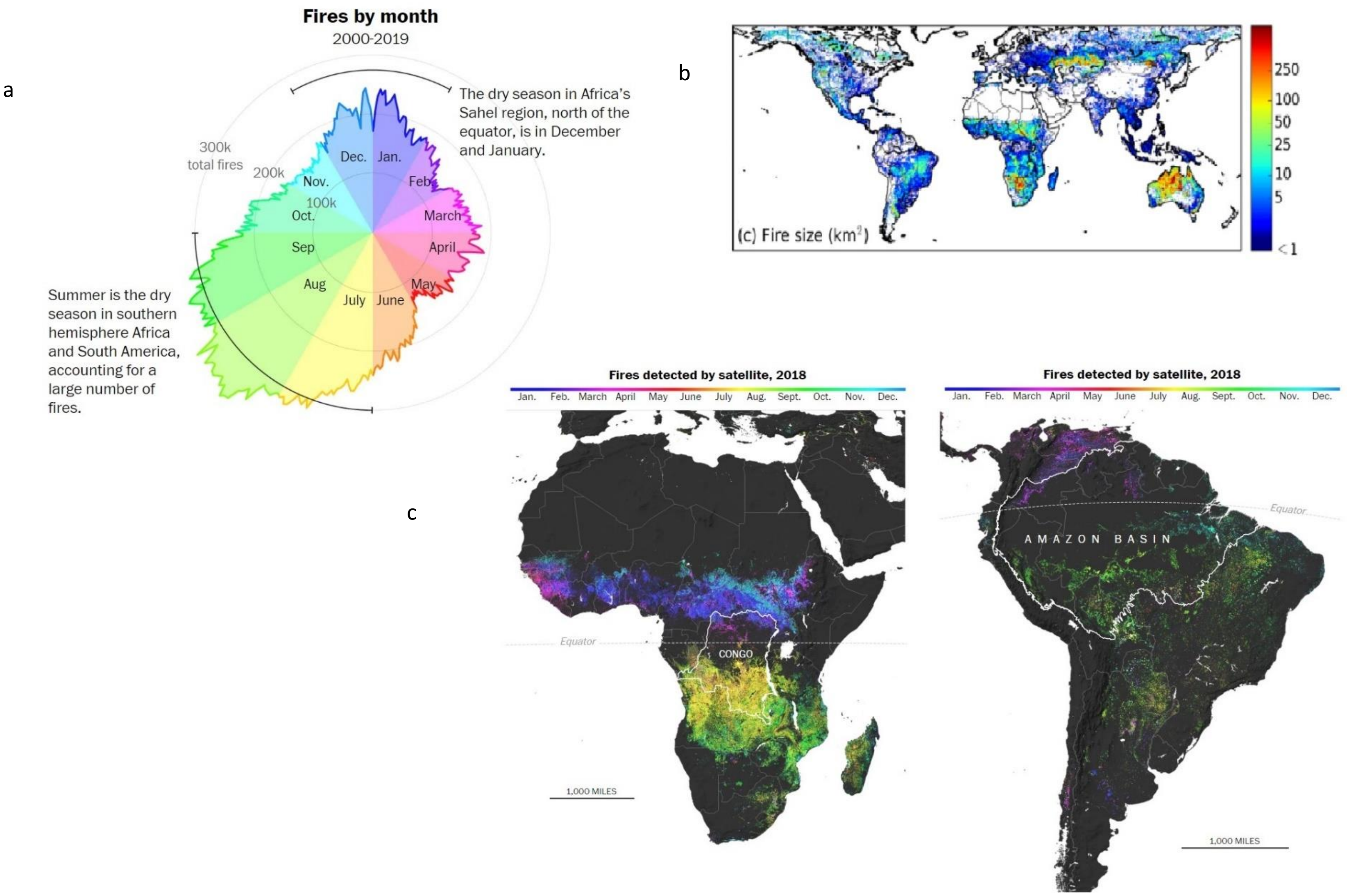


Fig 1. Global monthly distribution of fires using MODIS fire hotspots. Source: NASA


Fires by month

2000-2019

The dry season in Africa's Sahel region, north of the equator, is in December and January.

Summer is the dry season in southern hemisphere Africa and South America, accounting for a large number of fires.

Fires detected by satellite, 2018

Fires detected by satellite, 2018

Fig 2. Temporal distribution of fires in relation to fire counts, with a prominent contribution from Southern Hemisphere fires in Africa (Miombo and savannas), America (rainforests, dry forests and grasslands) and Asia (Australian savannas). Southern African and Australian host the largest burned areas (b) (Andela et al. 2017, FigS2 Supplement). Southern Hemisphere fires start approx. in June and until November (c) (NASA).

Results

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2025-2049, Dec-April dry season

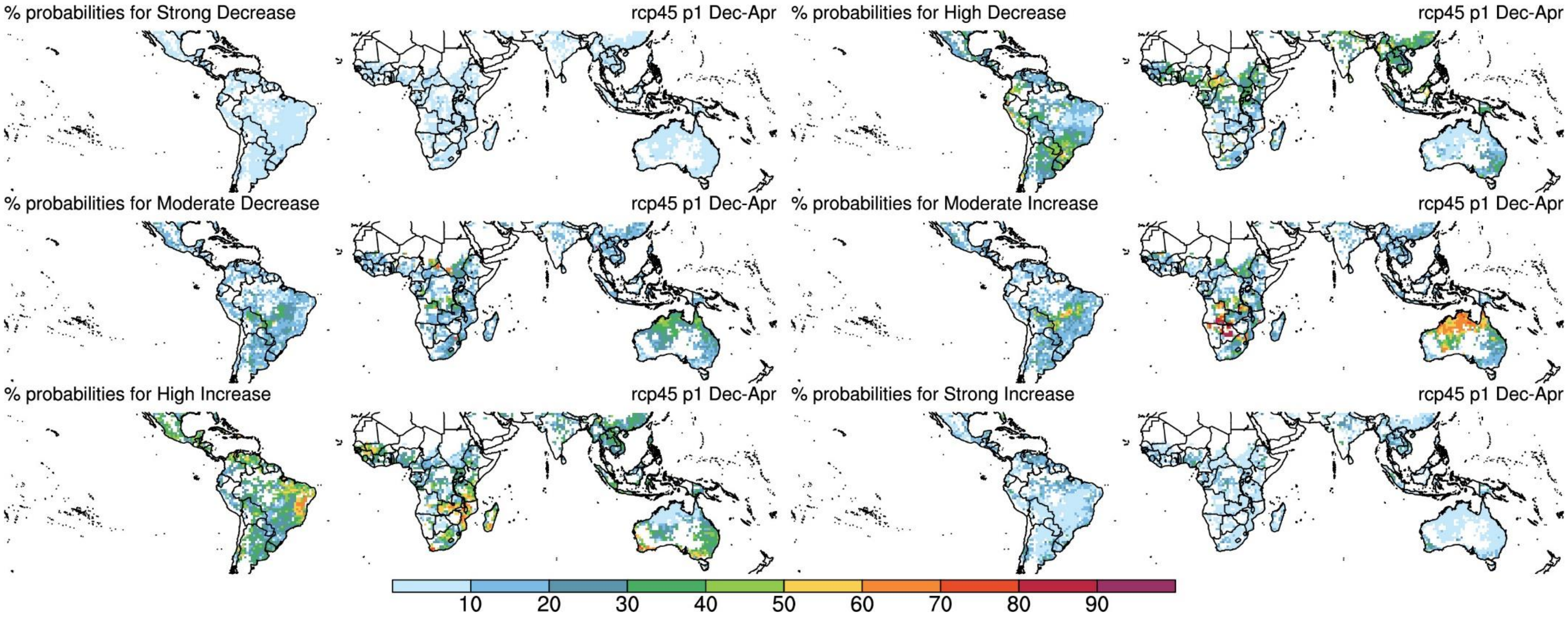


Fig 3. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2050-2074, Dec-April dry season

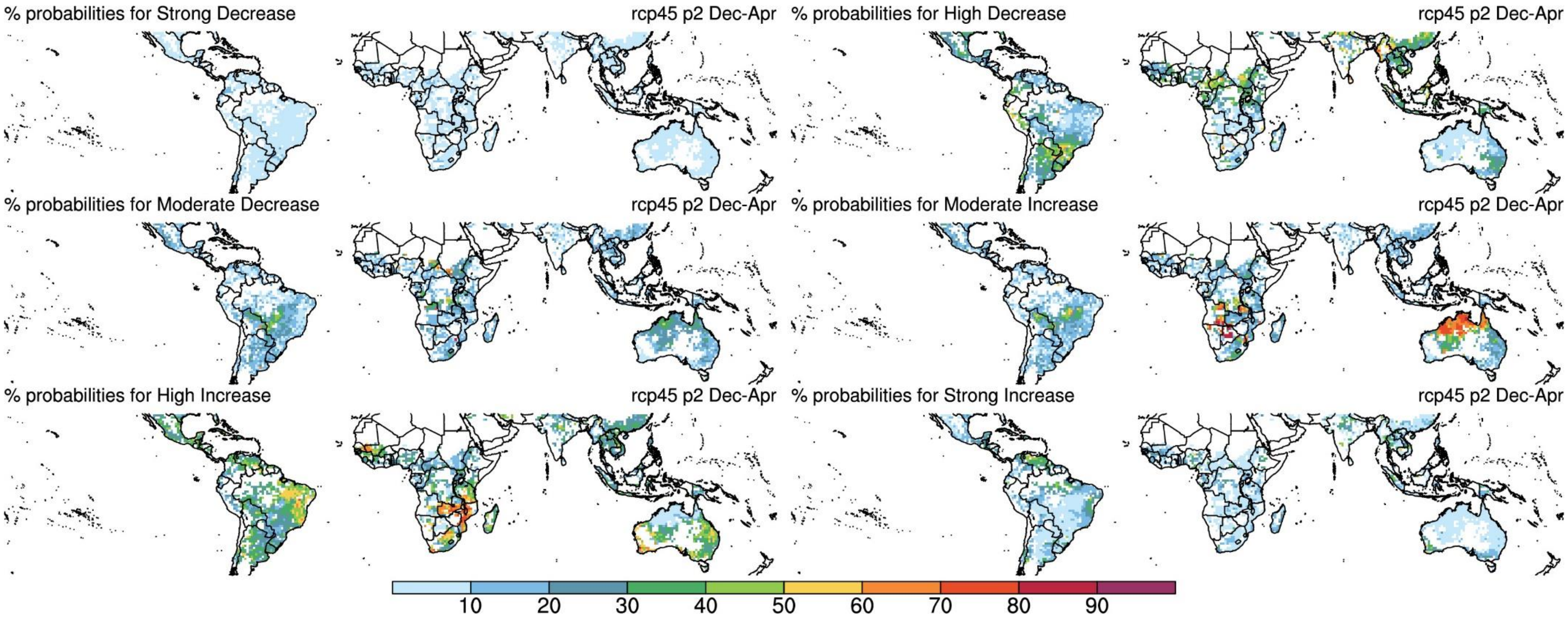


Fig 4. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2075-2099, Dec-April dry season

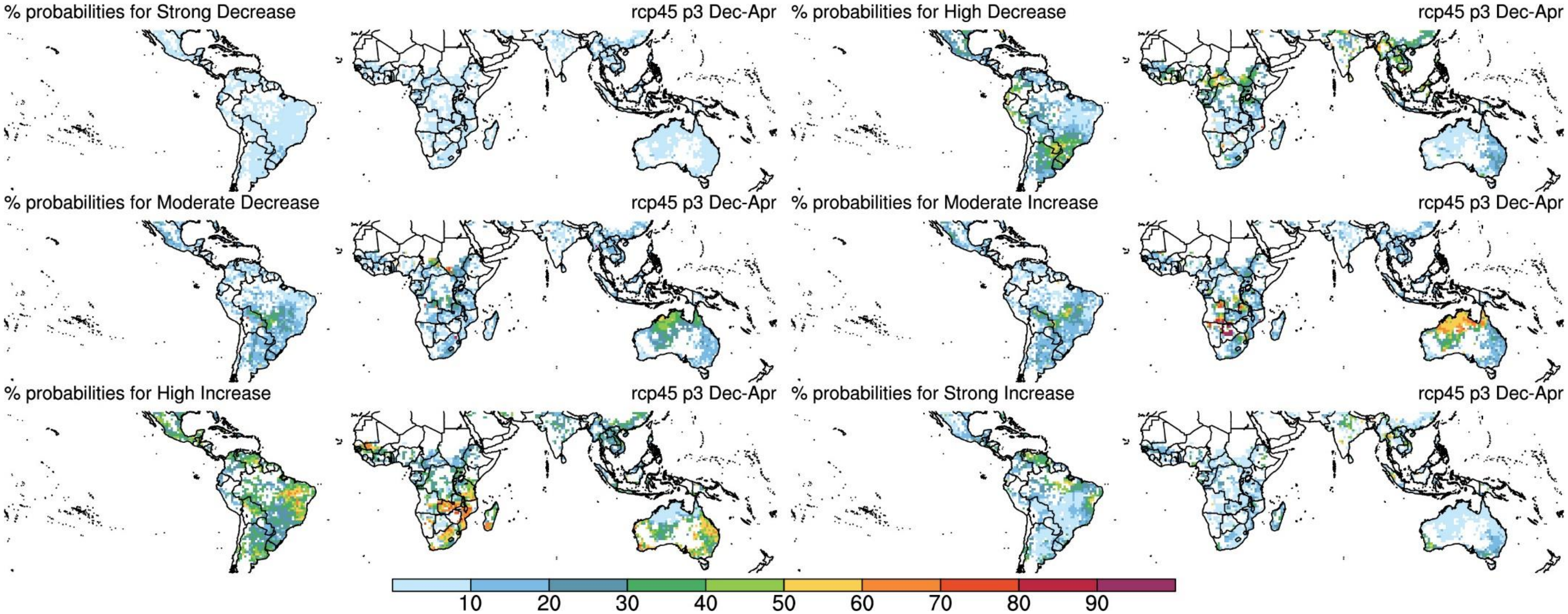


Fig 5. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2025-2049, May-Nov dry season

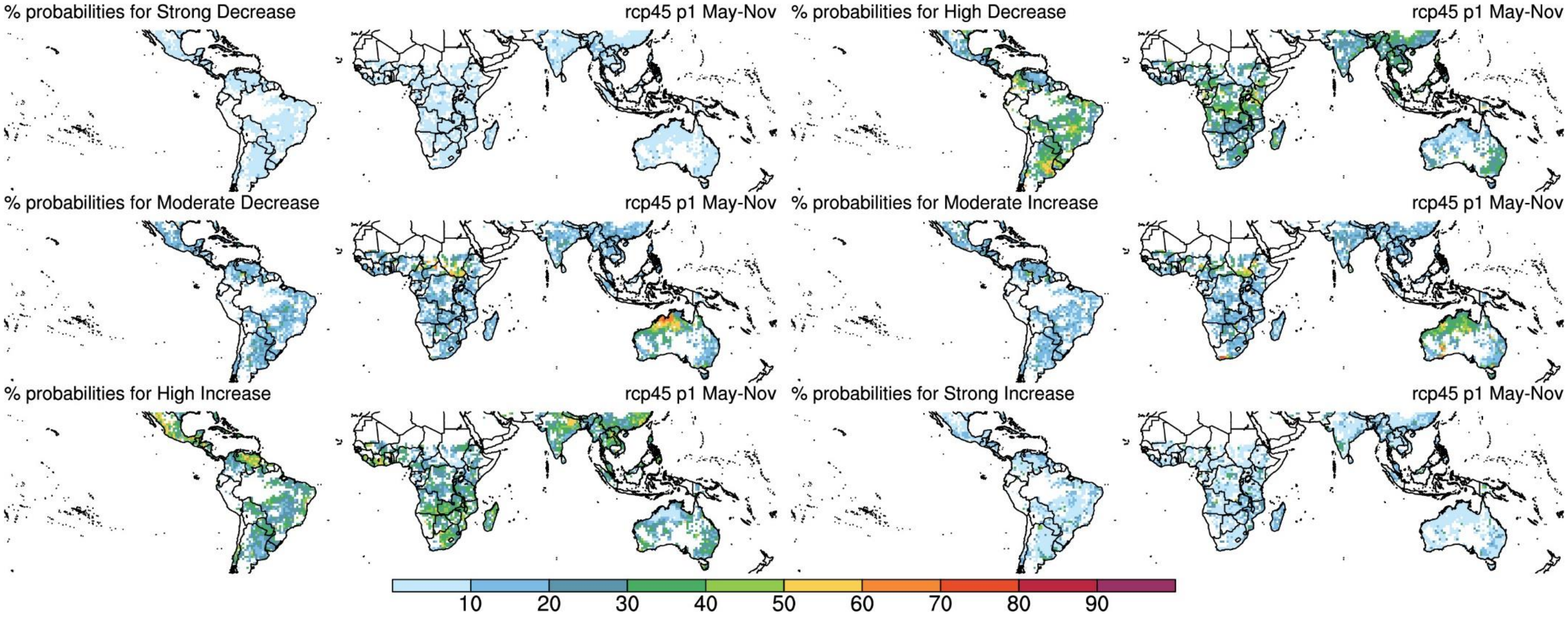


Fig 6. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60, p75, p90 (p40, p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2050-2074, May-Nov dry season

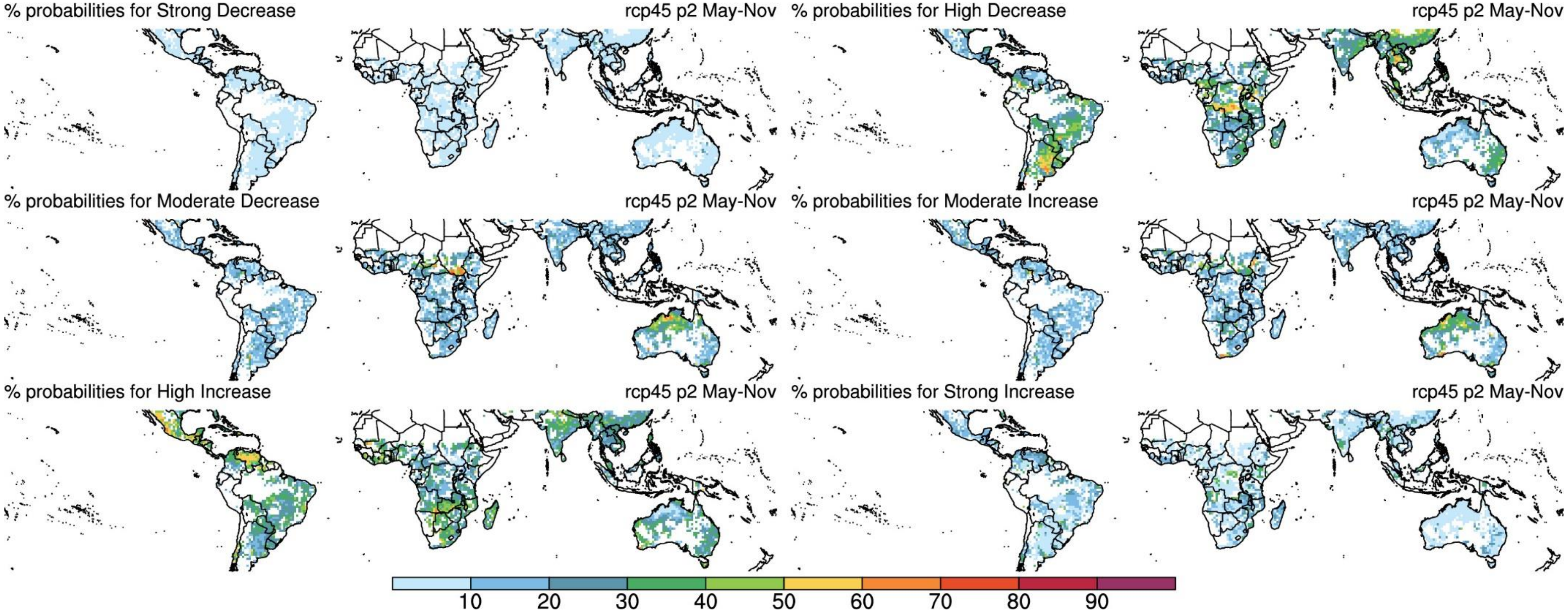


Fig 7. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP4.5 for 2075-2099, May-April dry season

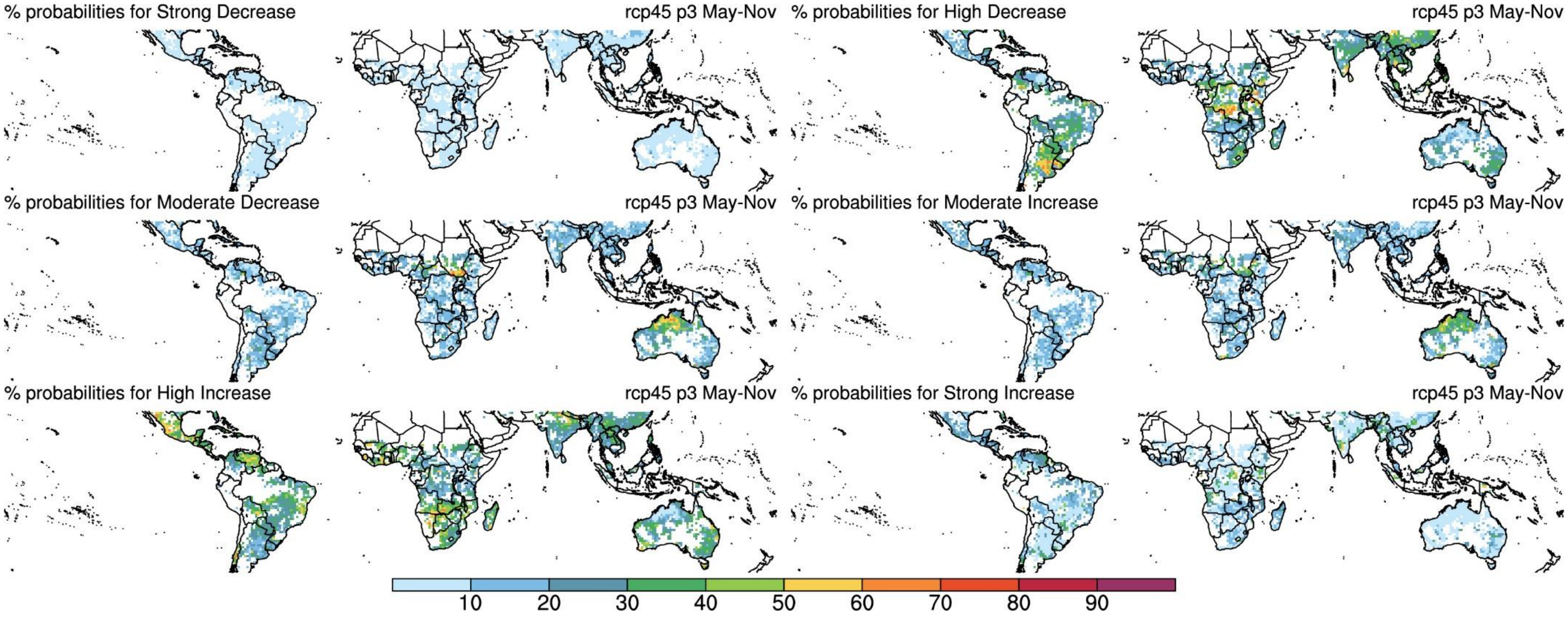


Fig 8. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2025-2049, Dec-April dry season

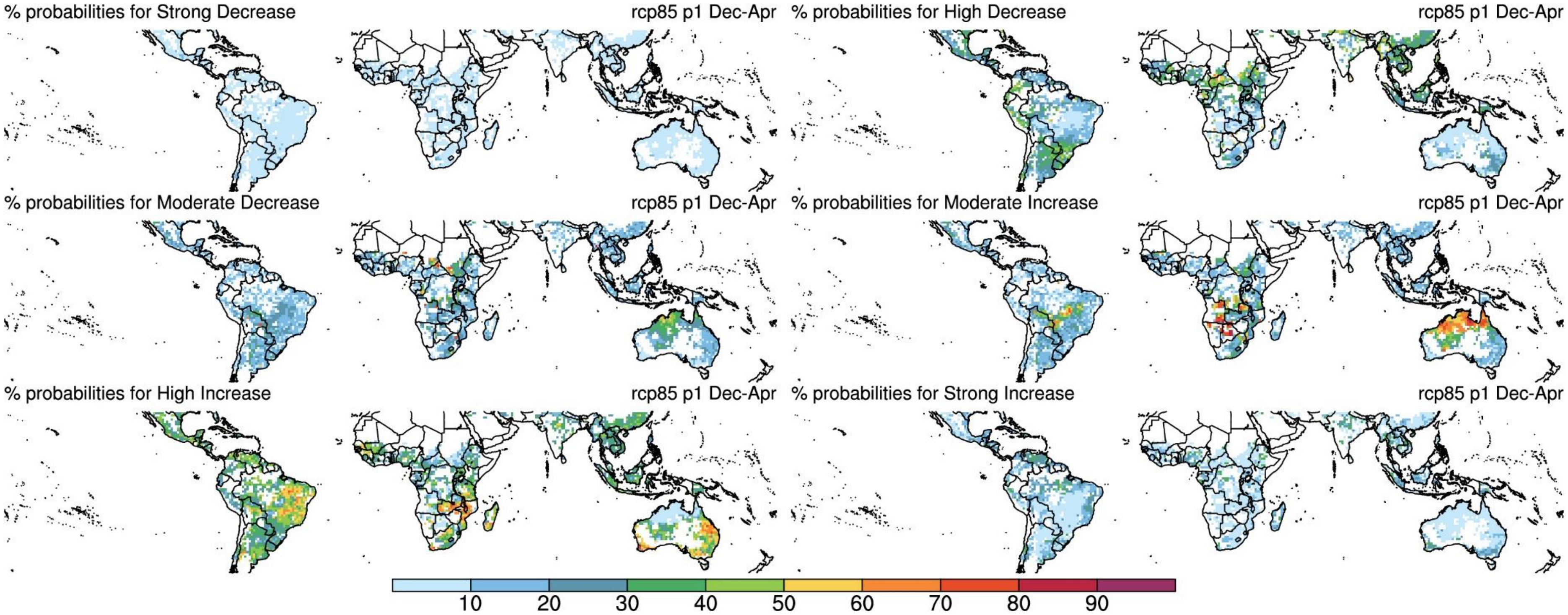


Fig 9. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2050-2074, Dec-April dry season

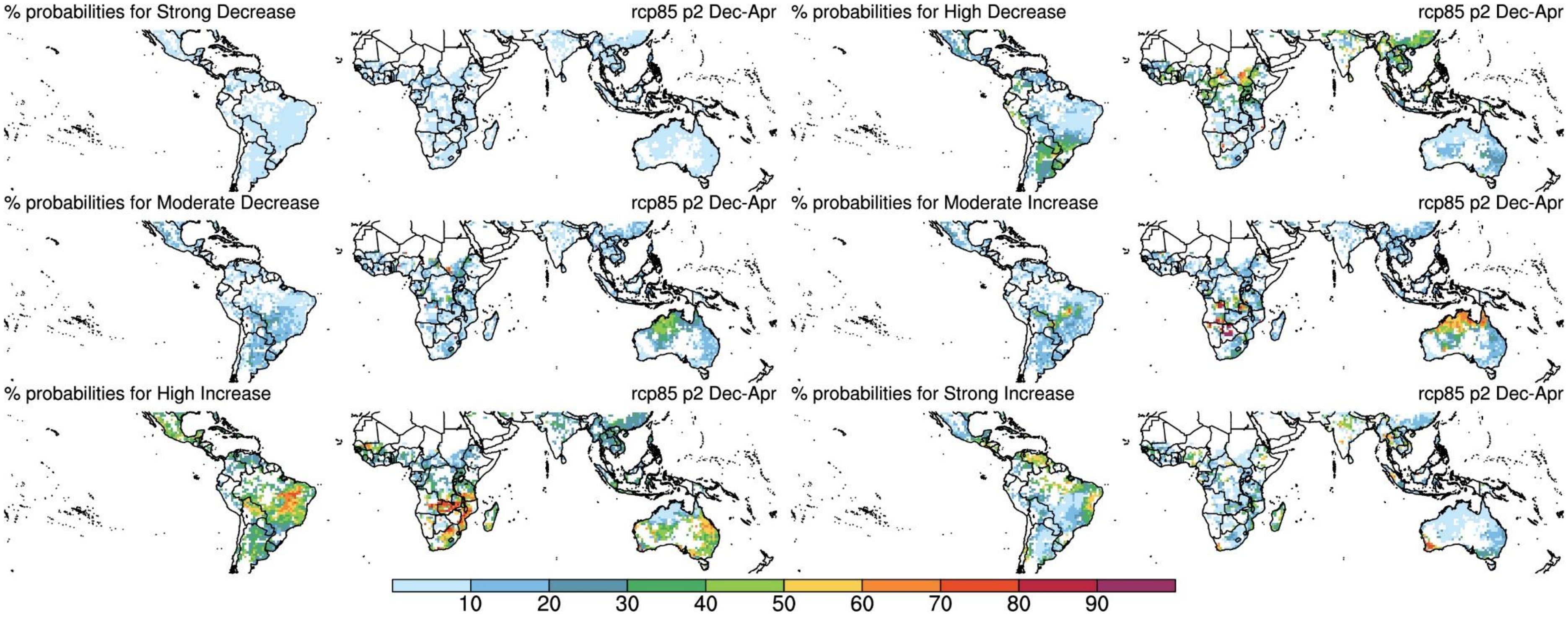


Fig 10. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2075-2099, Dec-April dry season

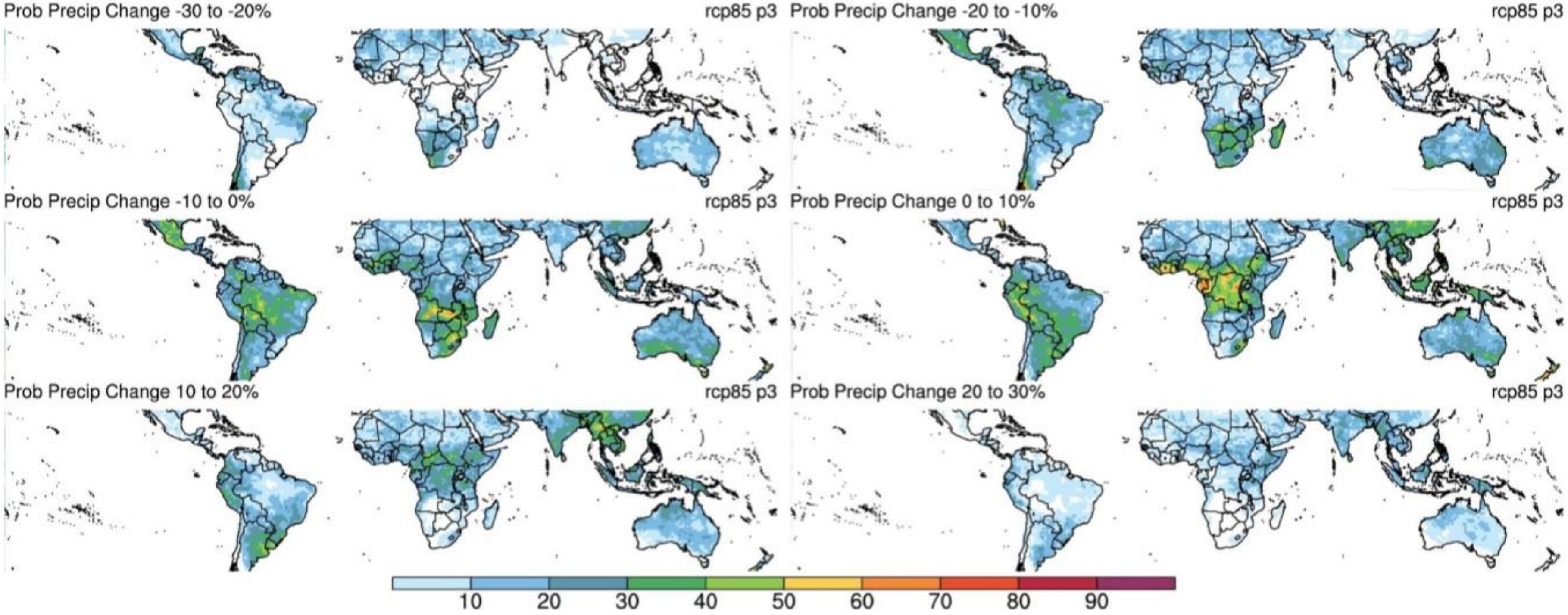


Fig 11. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2025-2049, May-Nov dry season

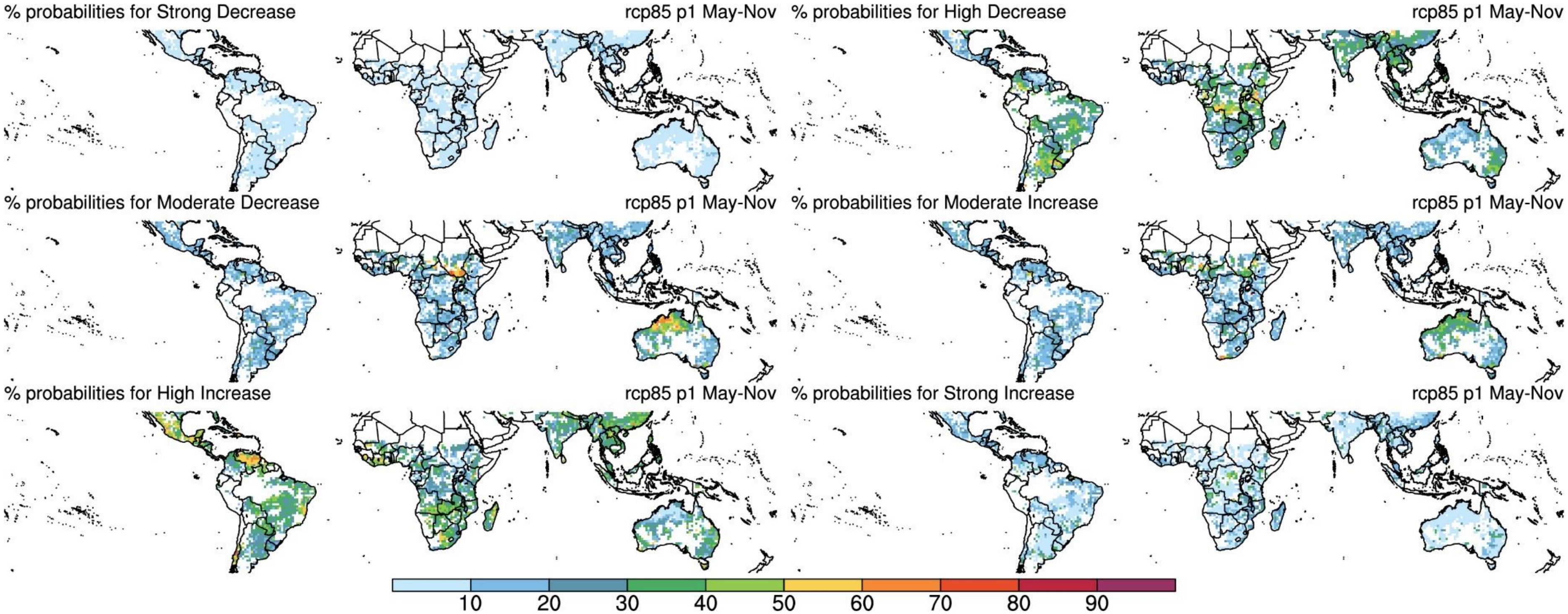


Fig 12. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2050-2074, May-Nov dry season

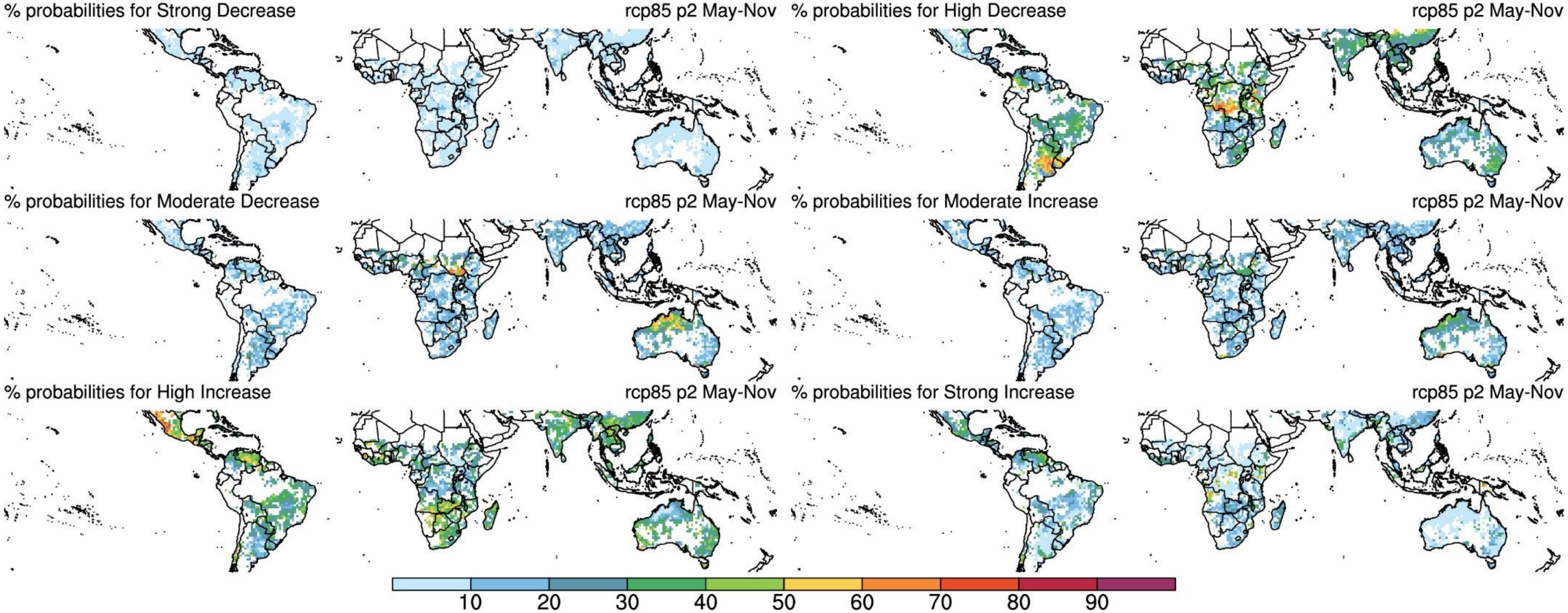


Fig 13. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

Fire Danger Probability (%) based on precipitation projections under RCP8.5 for 2075-2099, May-Nov dry season

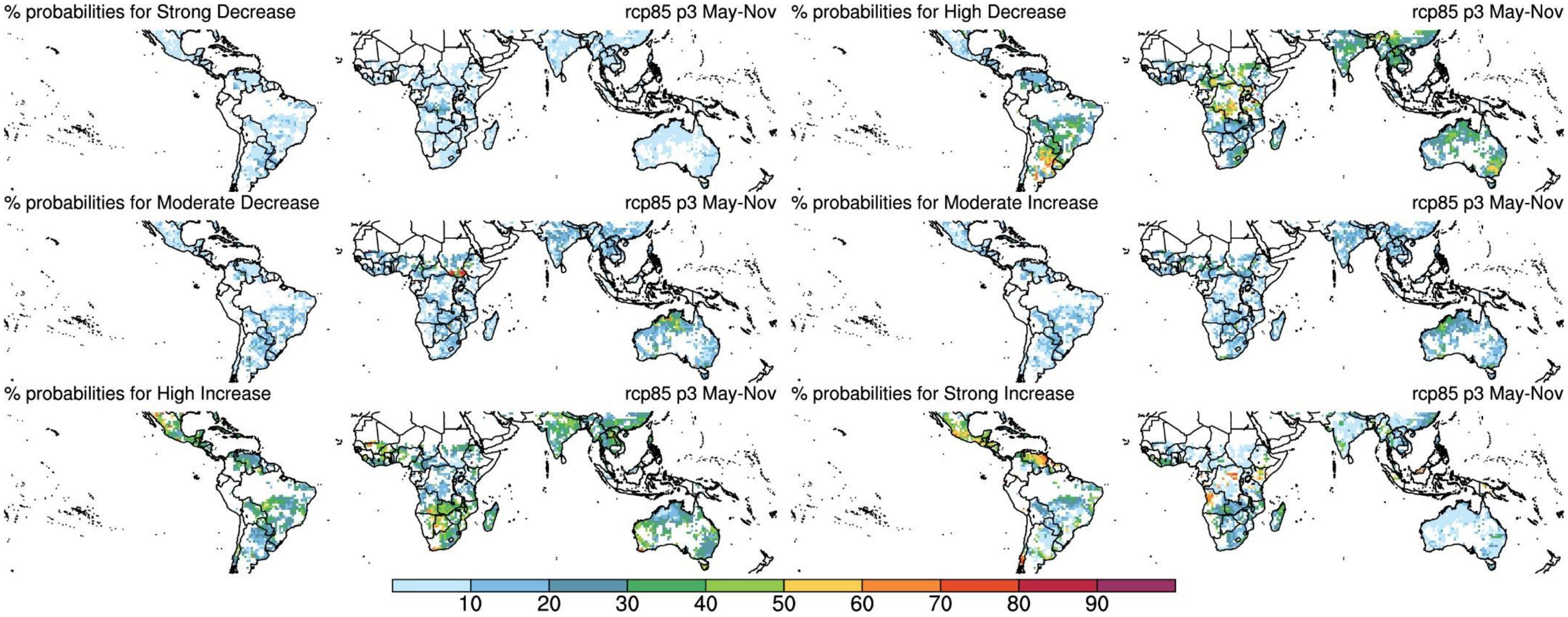


Fig 14. Probabilities of average burned area changes (increases/decreases), estimated as the number of model projecting changes for each interval. Increase/Decrease/Moderate/High/Strong intervals are defined as changes that reach percentiles p60,p75,p90 (p40,p25) in the historical period. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

	Africa	America	Asia	Notes
Temperature RCP4.5, 2025-2049 **Most changes at increase Temp. interval 1.0-1.5 C**	Saharan, Sub-Saharan and Southern Africa (prob. 70%)	Mexico, Peru, Eastern Brazil (prob. 70%)	Southern China, Southwestern, Eastern Australia (prob. 70%)	Dissimilar trends between development scenarios RCP4.5 and 8.5. Consistency along time periods with fading model projection agreement along time Not too informative
Precipitation RCP4.5, 2025-2049 **Most changes in intervals:** • **Precipitation Decrease 0-10%** • **Precipitation Increase 0-10%**	Decrease (-10-0%) Southern Africa (Zambia, S.Africa) Madagascar (70%) Western Africa (Ghana,Cote d'Ivore) (50%) Increase (0-10%) Central Africa (Congos, CAR, Camerun,Gabon) (70%) Sub-Saharan Africa (40-60%)	Decrease (-10-0%) Venezuela, Northern Brazil (50%). Mexico, North-Central Brazil (70%), Patagonia (90%) Increase (0-10%) Western South America (Peru, Ecuador, western Colombia). Southern Brazil-Uruguay, Northern Argentina (70%)	Decrease (-10-0%) Southern Australia (50-70%) Increase (0-10%) All South East Asia (Indonesia, Viet Nam, Myanmar), Southern China (70%) Northern, South-Eastern Australia (50-70%)	Consistent trends between RCP 4.5 and 8.5 with fading probabilities along time
Burned Area RCP4.5, 2025-2049, Dec-April dry season **Most changes in intervals:** • **High Decrease** • **Moderate Increase** • **High Increase**	High Decrease Sub-Saharan Africa (40-60%) Moderate Increase Central Southern Africa (Zambia, Angola, Botswana) (70-90%) High Increase Eastern Southern Africa (70-80%)	High Decrease Southern Brazil, central Peru (40-60%) Uruguay, Northern Argentina (30-40%) Moderate Increase Central Brazil, Northern Bolivia (50-60%) High Increase Eastern Brazil (50-70%), Venezuela (50%)	High Decrease Western Myanmar (50-70%) Southern China, Viet Nam, south Eastern Australia Moderate Increase Northern Australia (70-90%) High Increase South-western Australia (50-70%), parts of central-eastern Australia (50%)	Consistency between RCP4,5 and 8.5 with fading probabilities along time Higher probabilities for projected changes in Dec-April dry season fires Probabilities of increase are higher than probability of decrease Different spatial locations for fire danger probabilities for Dec-Apr than for May-Nov

Table 1: summary of Temperature, Precipitation and Burned area projections focusing on the highest probabilities: RCP4.5, season Dec-April, and time period 2025-2049)

Table 1 summarizes the countries most affected by the projected trends in Temperature (Annex), Precipitation (Annex) and Fire danger (burned areas) (Figure 3 to Figure 14) for ca. 2050, RCP4.5 and fire season Dec-Apr. The level of agreement of the different projections was higher for the closest time period 2025-2049 and the more conservative RCP4.5 concentration pathway. Moreover, projected fire danger for Dec-April showed the highest agreement in the probability of change, against May-Nov, that saw less agreement. Projected trends were consistent among RCPs and time periods with fading probability agreements, in both cases. Temperature was rather uninformative with most agreed changes happening on an interval of temperature increase (1.0-1.5C) that is already occurring in present time. This result did no help us confirm Pechony and Shindell (2010)'s predictions that temperature may lead fire trends in the future. For precipitation, models mainly agreed in moderate changes (increases/decreases) around 10% of historical period values.

Fire danger projections

The projections for Fire danger followed those of precipitation and showed increases and decreases, with **higher agreement in increasing burned areas than in decreasing for the near future**. This result goes against currently observed decreasing burned area trends (Andela et al. 2017). **The highest agreement of increasing fire danger strongly focused on tropical dry ecosystems (forests and woodlands)** with moderate increases projected for the Southern African (Zambia, Angola, Botswana) Miombo and woodlands, northern Australian woodlands and savannahs, and central-eastern dry Cerrado forests in Brazil (all of them with 70-90% of agreement). High increases in fire danger also focused on dry forests and mainly affected the dry Cerrado forests in Eastern Brazil and the Miombo forests of Eastern-Southern Africa (all of them with 70-90% of agreement).

Burned area projections (moderate increase) closely matched currently observed trends of increasing burned areas in Southern Africa (miombo) (Andela et al. 2017) (Figure 15a,b), **agreed with the importance of fire in Brazilian Cerrado,** although more to the west that currently observed, but **disagreed with the observed decreasing trends in Northern Australian** (woodlands and shrubs). Contrarily, our fire danger projections highly agree on moderate increase of burned area in Northern Australia for ca. 2050 (Figure 15ab), with no decreasing trend (Figure 16c)

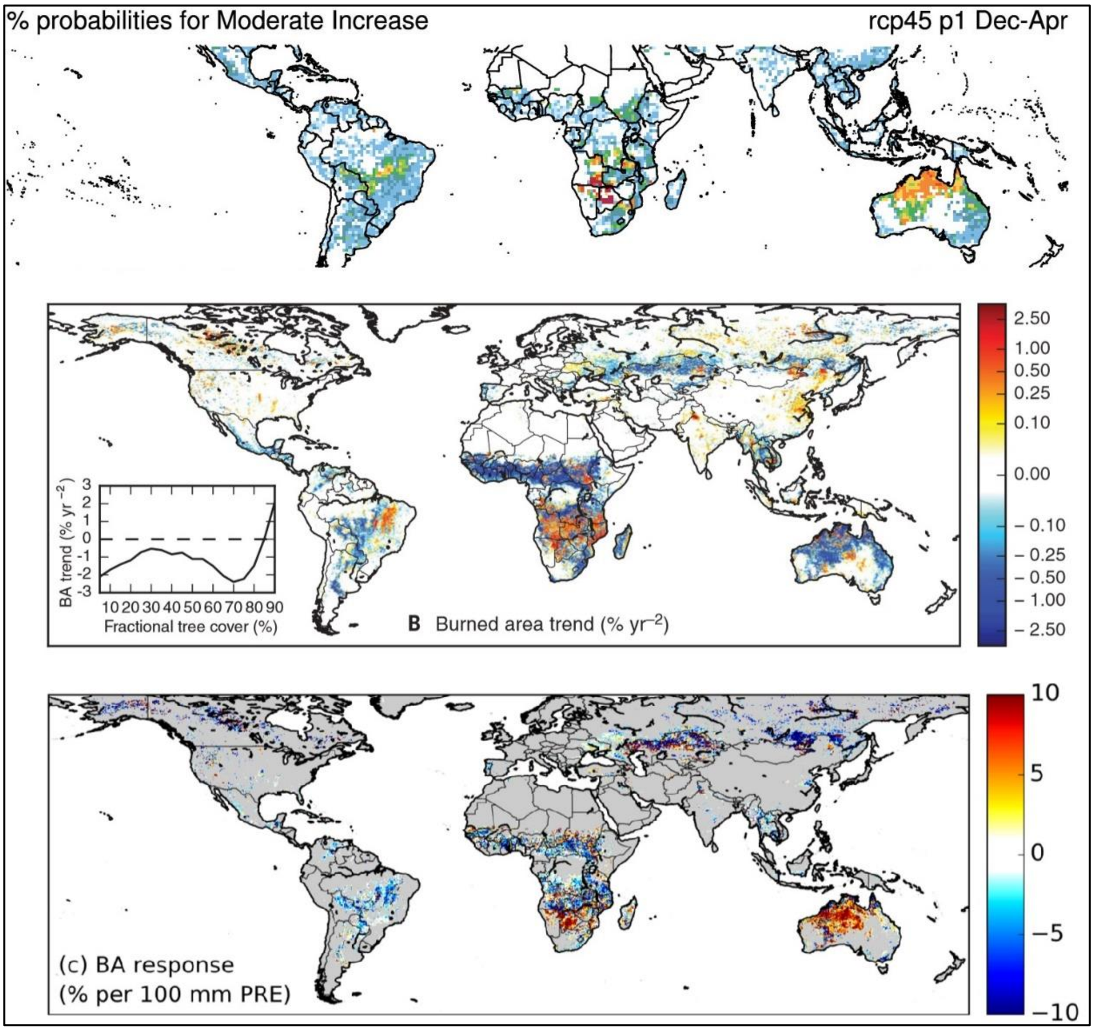


Figure 15: Fire danger projections for 2025-2049, for Dec-Ap, RCP4.5 (a), current trends of burned area 1998-2015 (Andela et al. 2017) (b), response of burned area per 100mm change in precipitation (Andela et al. 2017) (c)

Precipitation-induced variation and trends

Precipitation projections led fire danger in two directions: Negative correlations between precipitation and burned areas (decrease in burned area with increased precipitation) were observed in forested and wet grassland areas (e.g. Peru, Southern Brazil-Uruguay, Northern Argentina, South Eastern Asia and China) (Figures 15c&16c), while positive correlations (increased burned area with increased precipitation) affected low fuel xeric ecosystems (e.g. Sub-Saharan Africa) (Figures 15c&16c). Thus, high levels of precipitation prior to the onset of the fire season may increase fire activity in arid regions because greater moisture availability enhances herbaceous biomass production and thus fuel build-up and continuity, whereas higher levels of precipitation during the fire season may suppress fires because of increases in fuel moisture. Both effects can occur within the same region, with their relative importance depending on the timing and magnitude of precipitation anomalies. Time-wise, precipitation has a negative correlation with burned area on short lead times in humid savannas and tropical forests and a positive correlation over longer time scales in more xeric savannas and grasslands (Andela et al. 2017).

Comparison with other Fire projections

Our fire danger predictions matched surprisingly well the very differently produced scenarios of future fire activity by Pechony and Shindell (2010) who used the GISS GCM model and three IPCC development scenarios (A2, A1B, B1): from a more aggressive development and population growth scenario (A1) to more environmental and reduced human pressure scenario (B1). Particularly close to scenario A1, our fire danger projections agreed with a decrease of Sub-Saharan fire activity, as well as less fire in Western South America (Peru), Southern Brazil-Uruguay and Northern Argentina. Similarly, our projected fire danger agreed with an increase of fire activity in Southern and Eastern Southern Africa, increases in Australia (generalized increase in the GISS model), and increases in western Brazil (border Bolivia-Brazil), Eastern-Brazil, and Venezuela.

Pechony and Shindell (2010)’s GISS GCM climate simulations, like other models, predict a significant warming over the forth coming century. Rapidly rising temperatures and regional drying reverse the recent fire activity decline, driving a rapid increase after∼2050 in all three scenarios examined there (A2, A1B, B1). Population growth, and to a lesser extent, land-cover change reduces the increase in fire activity, but does not reverse the long-term trend, even in the A2 scenario where anthropogenic pressure is strongest and continues to increase throughout the simulations. Ironically the more “optimistic” A1B and B1 scenarios that produce milder warming result in greater biomass burning due to reversal of land conversion and declining population (and hence fire suppression).

Highlights

- Currently observed (1998-2015) and projected (2025-2049) hotspots of fire activity (burned area) all agree on a disproportional pressure over dry ecosystems, (Miombo, Cerrado, woodlands, shrublands) which will most likely have consequences for land desertification, water security and human migration.

- There is generally good agreement between currently observed trends of burned area (1998-2015) and projected hotspots of fire danger in Africa (same geographical region) and America (same ecosystem) the biome) but full disagreement in Asia, particularly on the trend of northern Australian Savannahs which our projections agree on increased fire danger while current trends show a clear decrease.

- While precipitation is an undisputed key driver of global fire, land activities and population dynamics also influence fire trends (particularly when climate is moderate). Next steps should investigate how human and economic development could be modelled to predict future fire activity and hotspots of fire danger.

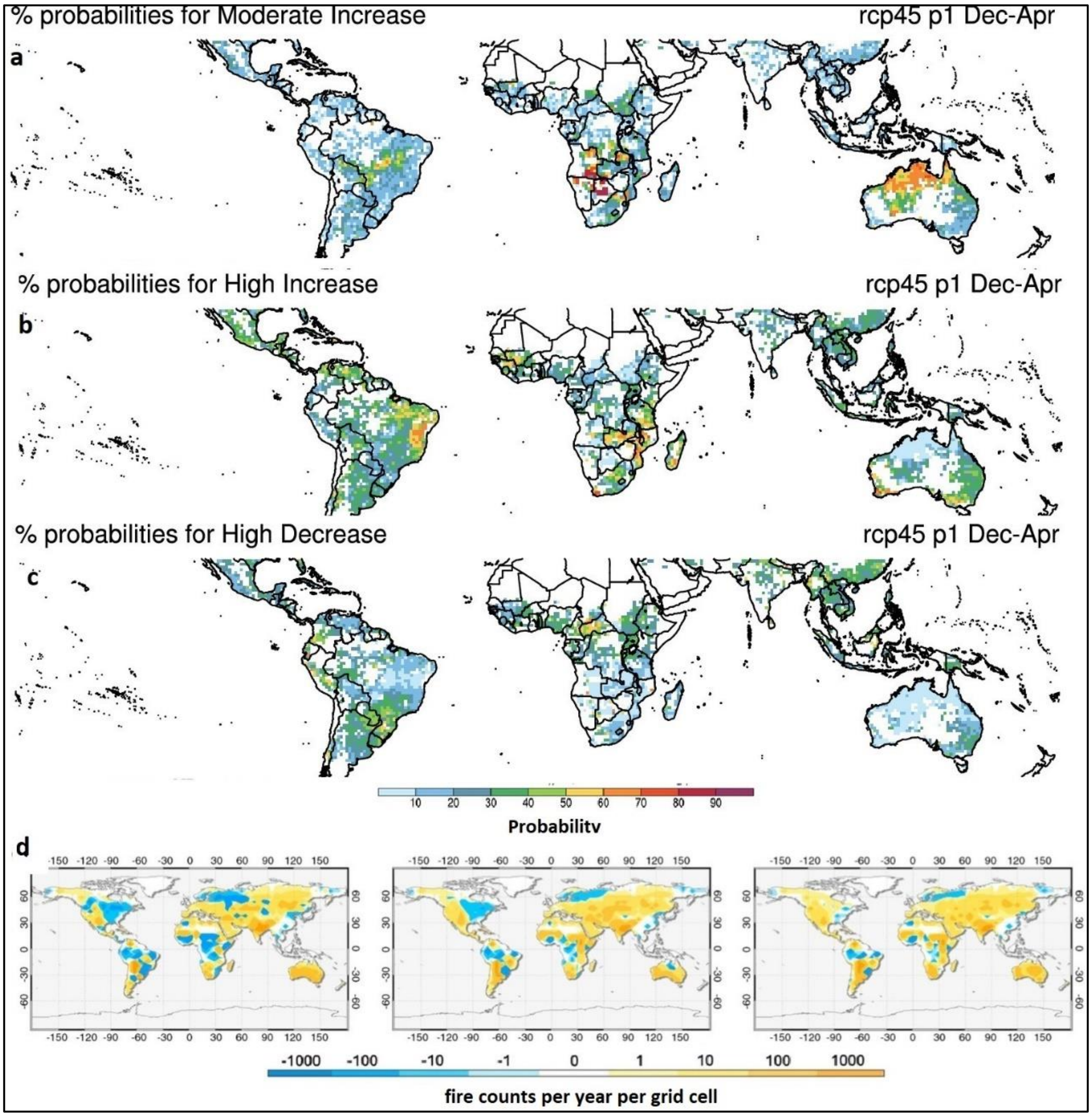


Figure 16: Fire danger projections for Increased burned area (Moderate and High) and Decreased burned area (High Decrease) in 2025-2049 contrasted to Pechony and Shindell (2010) projected fire activity

Plausible risk reduction activities

Our future fire risk scenarios are climate-driven. Therefore, activities on risk reduction concentrate on fire prevention measures that affect fuels and ignition sources in wildfires. Our focus is on forest fires outside the urban interface. Following contemporary wildfire management planning, **fire management prevention rather than suppression must be prioritized** when planning future fire risk reduction programs. Prevention is the most effective and efficient approach to reduce fire risks.

After its ignition, a forest fire will spread when assisted by continuous flammable material, both horizontal and vertical, and by weather conditions, primarily strong winds, low humidity and high temperatures. Prevention measures focus, therefore, on reducing fuel loads, fuel continuity, and fuel flammability. Good infrastructure also helps minimize the area a fire spreads to, such as access roads and water supply, above all, and early detection of the fire

A list of plausible fire prevention activities would focus on human ignitions and fuel risk reduction:
Ignition sources reduction

- Fire banning in high fire risk areas during high risk time windows
- Physical barriers to discourage human presence
- Well maintained electric lines

- Well maintained railway lines

Flammability reduction

- Reduce flammability levels and rates of consumption by planting trees and shrubs with low flammability rates and slow consumption rates
- Use low flammability species as barriers and fire deterrents in fire breaks, and planted forests.
- Promote landscape mosaics of low flammability species to act as fire deterrents to allow fire attack.

Fuel load reduction

- Reduce fuel loads in plantations that can act as fire breaks by regulating the frequency of planted sapling rows. For firebreaks on summits and ridges, trees are planted sparsely with low, spreading shrubs planted among them.
- Grazing of understory fuels. In forests where there are slow growing species, especially broadleaves, grazing requires management on timing and frequency.
- Control herbicide spraying
- In mature forests forest, fuel reduction includes forest sanitation (removal of dead/desiccated/sick trees from the forest), thinning (removing the less developed trees and the withering trees), pruning (removal of lower branches of a tree up to a third of its height) and removal of the cuttings and the tree waste

Fuel continuity reduction

- Promote forest isolation through firebreaks and grazing lines.
- Prescribed burning

Fire prevention infrastructure

- Water supply network
- Watchtowers
- Sign posting to support fire attack

References

Andela et al (2017) A human-driven decline in global burned area. Science 356, 1356–1362

Jolly et al. (2015) Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications 6:7537

Pechony and Shindell (2010) Driving forces of global wildfires over the past millennium and the forthcoming century. PNAS,107,19167–19170

Annex

CMIP5 Temperature Change Probabilities (%) under RCP4.5 for 2025-2049

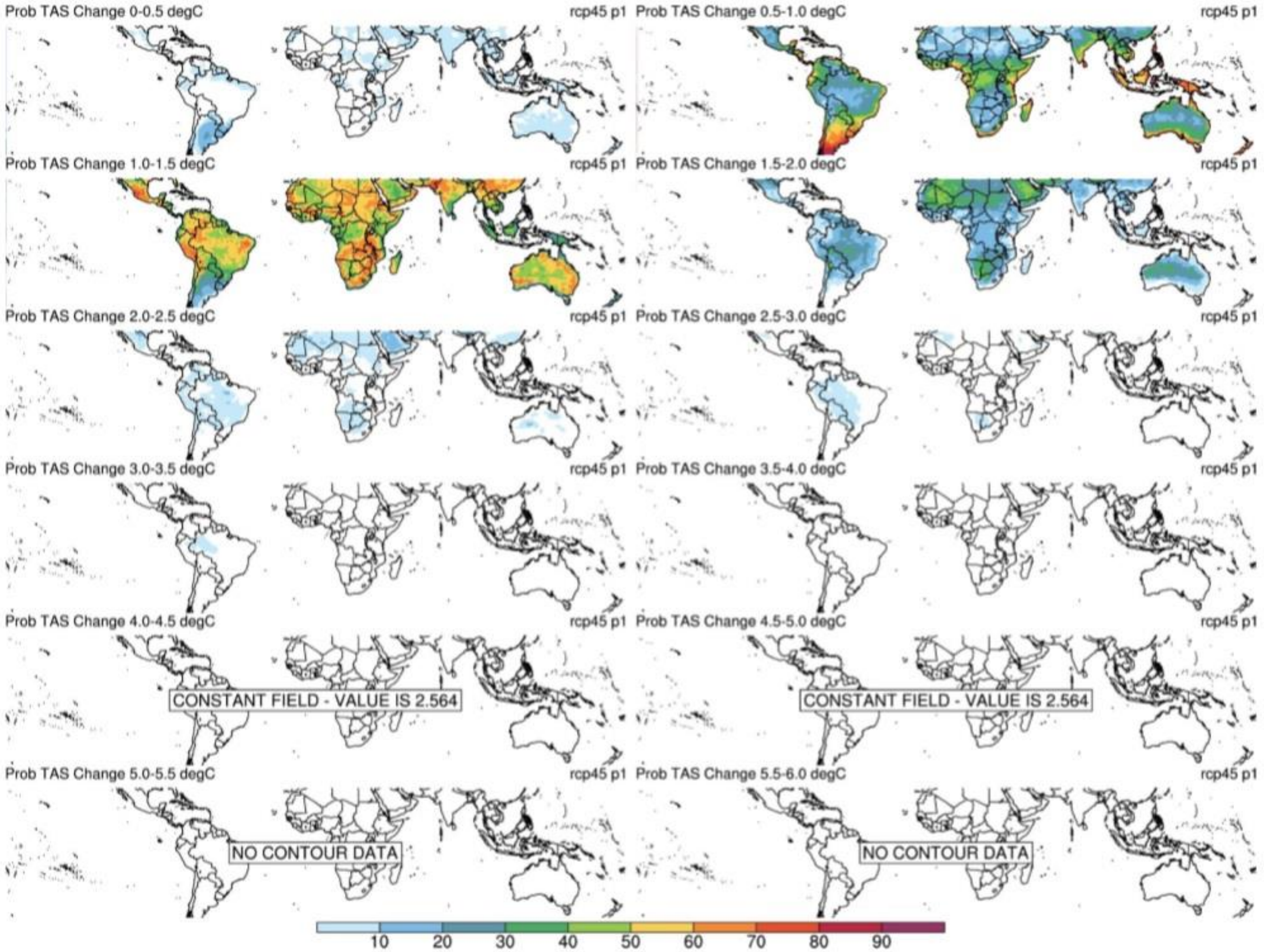


Fig 1. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Temperature Change Probabilities (%) under RCP4.5 for 2050-2074

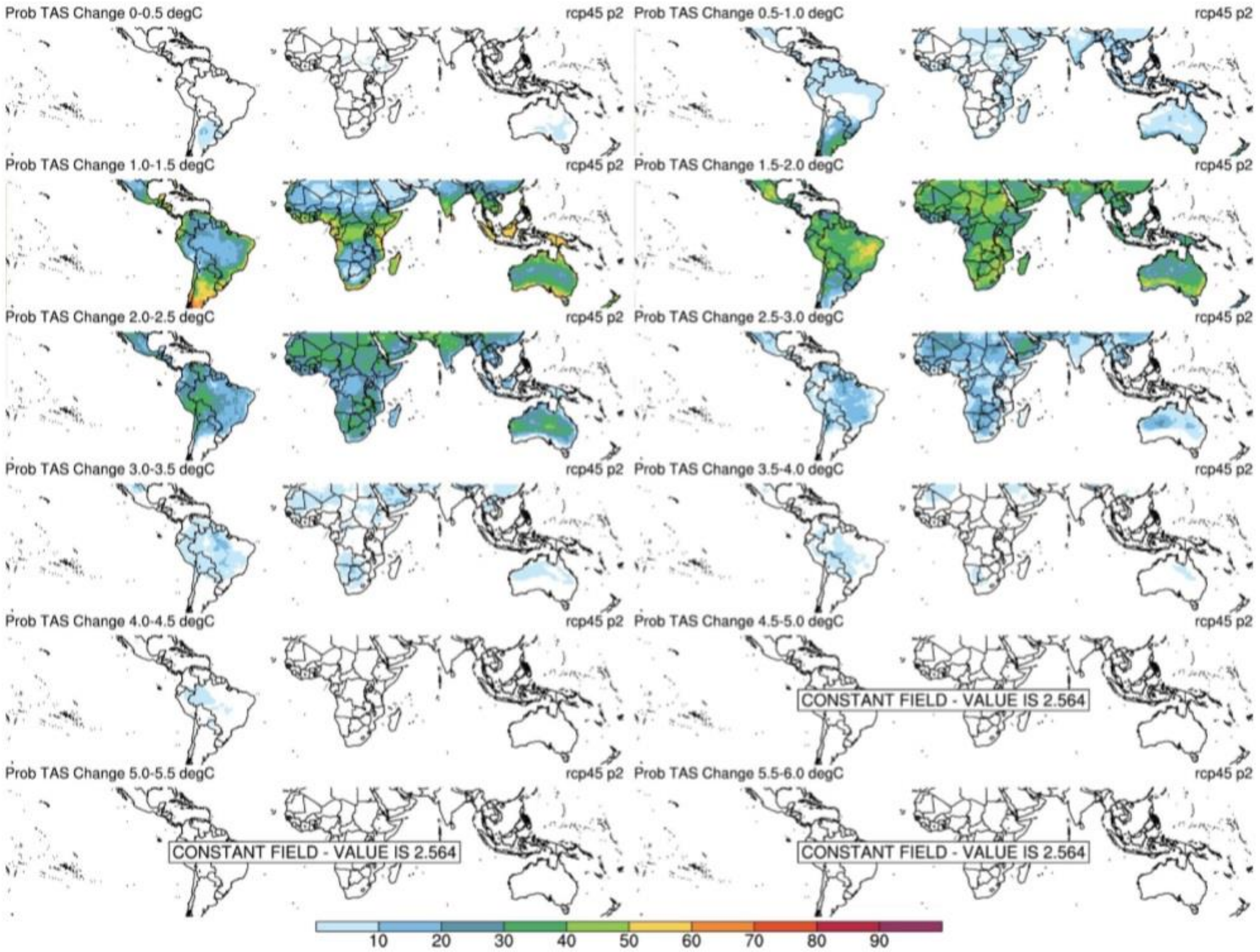


Fig 2. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

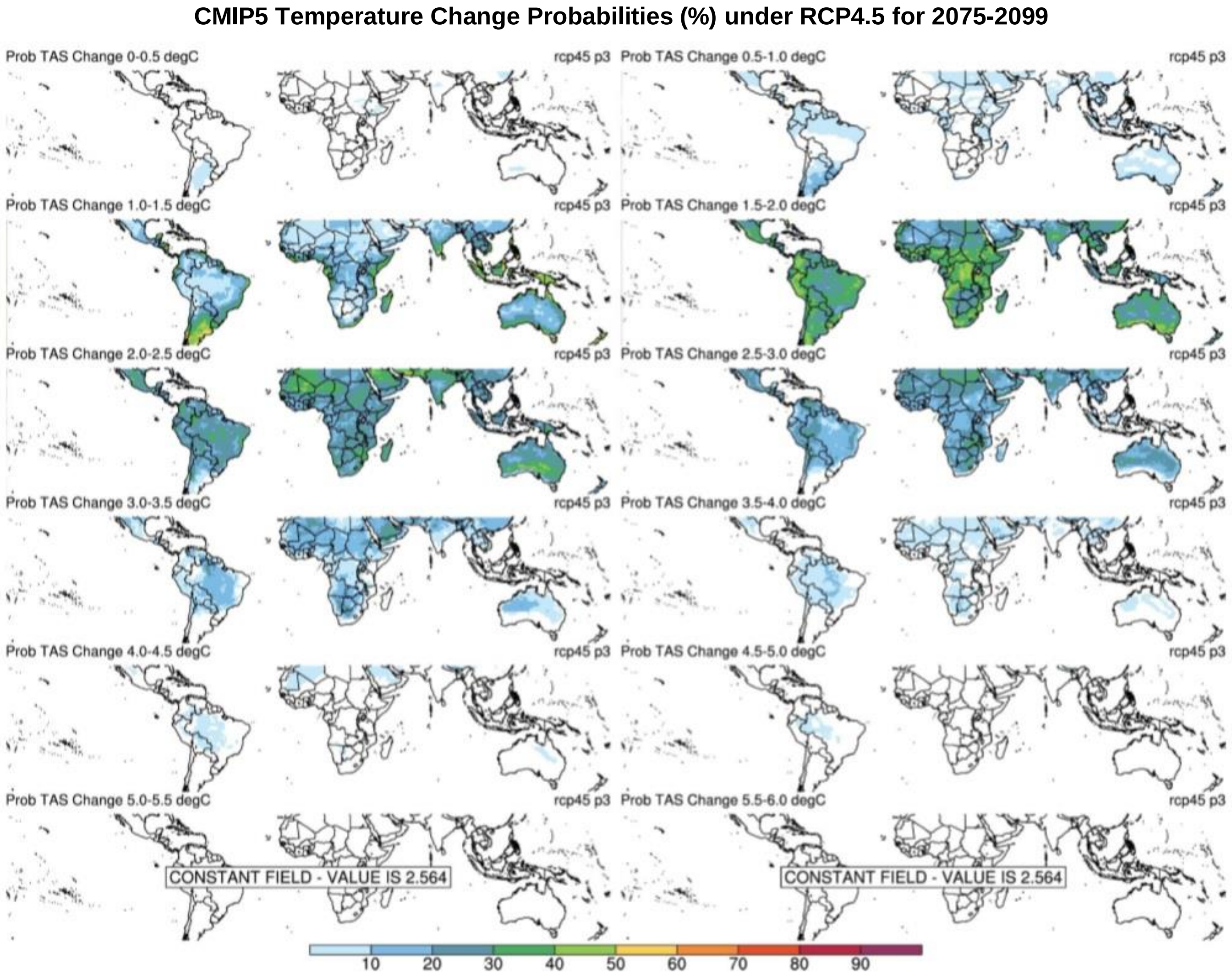


Fig 3. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Temperature Change Probabilities (%) under RCP8.5 for 2025-2049

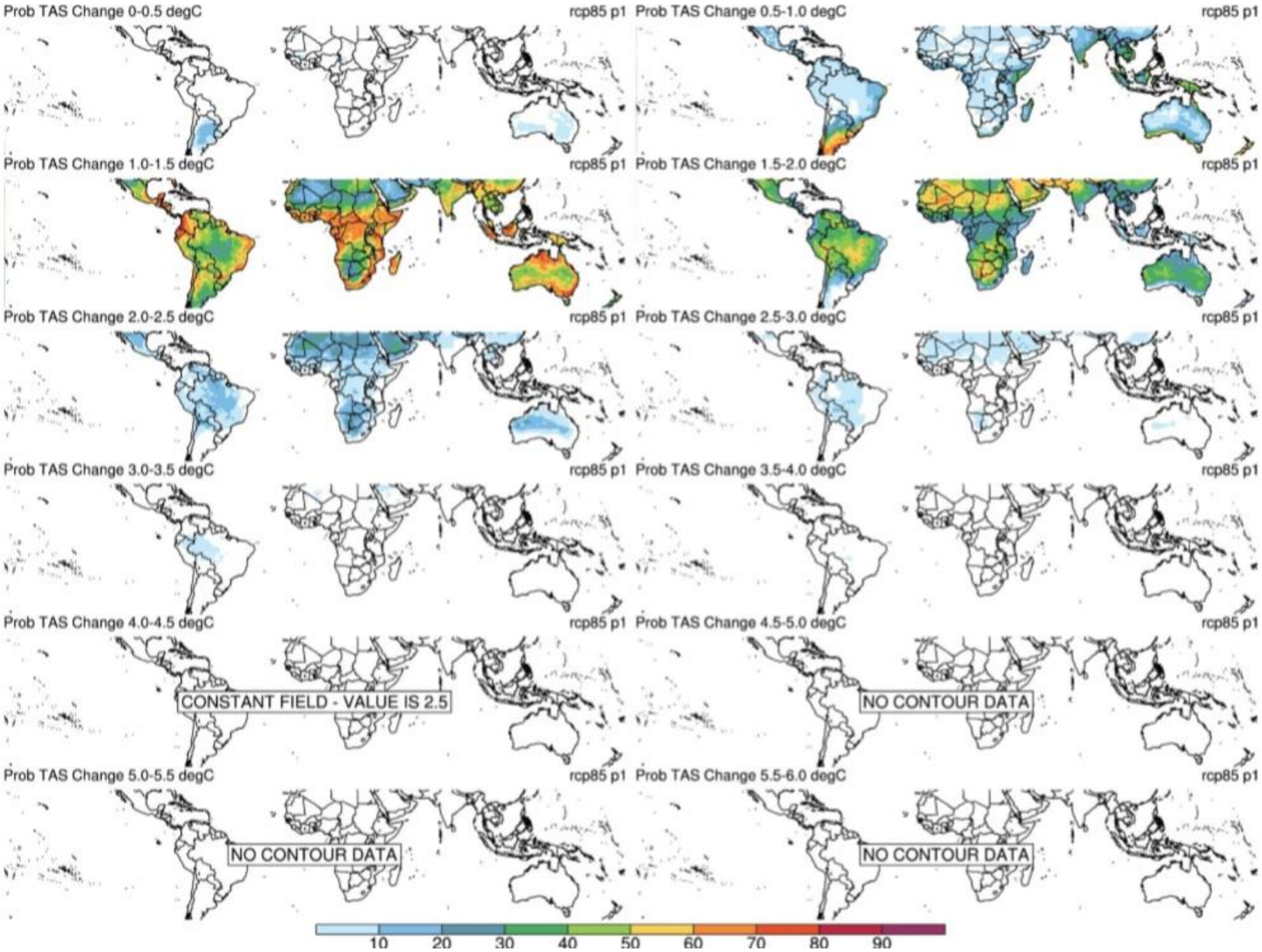


Fig 4. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Temperature Change Probabilities (%) under RCP8.5 for 2050-2074

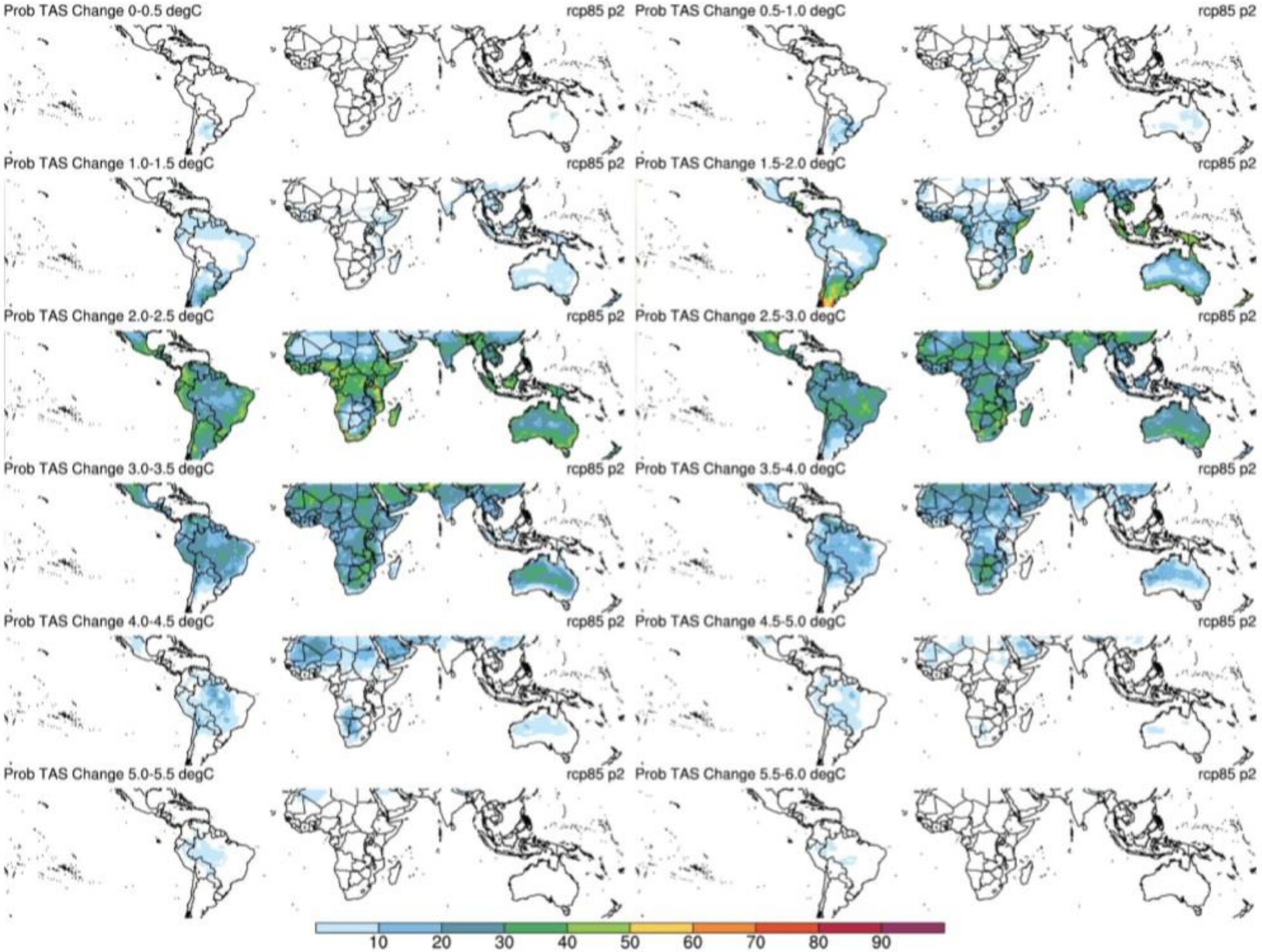


Fig 5. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Temperature Change Probabilities (%) under RCP8.5 for 2075-2099

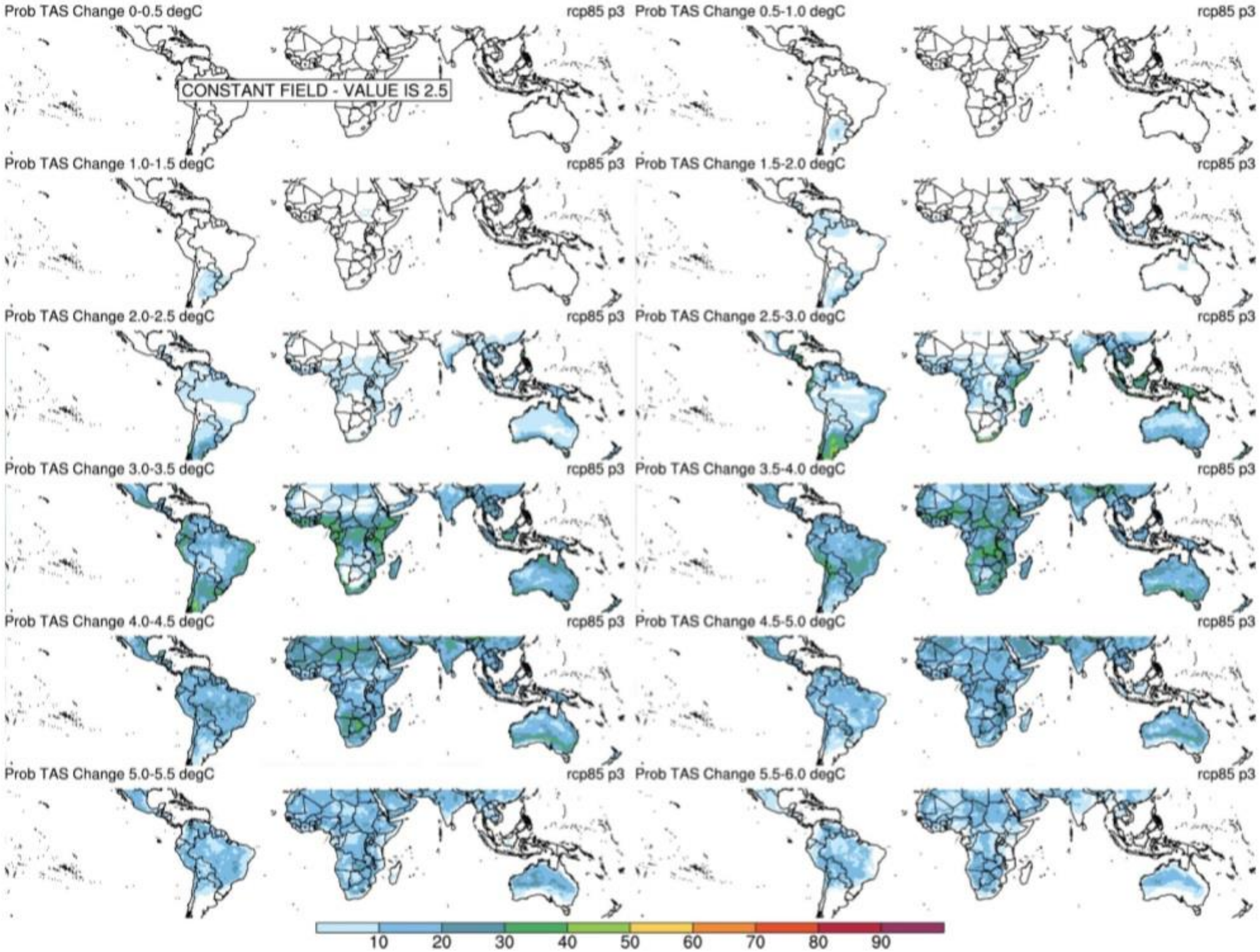


Fig 6. Probabilities of temperature increases by intervals (0.5-6 C degrees), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP4.5 for 2025-2049

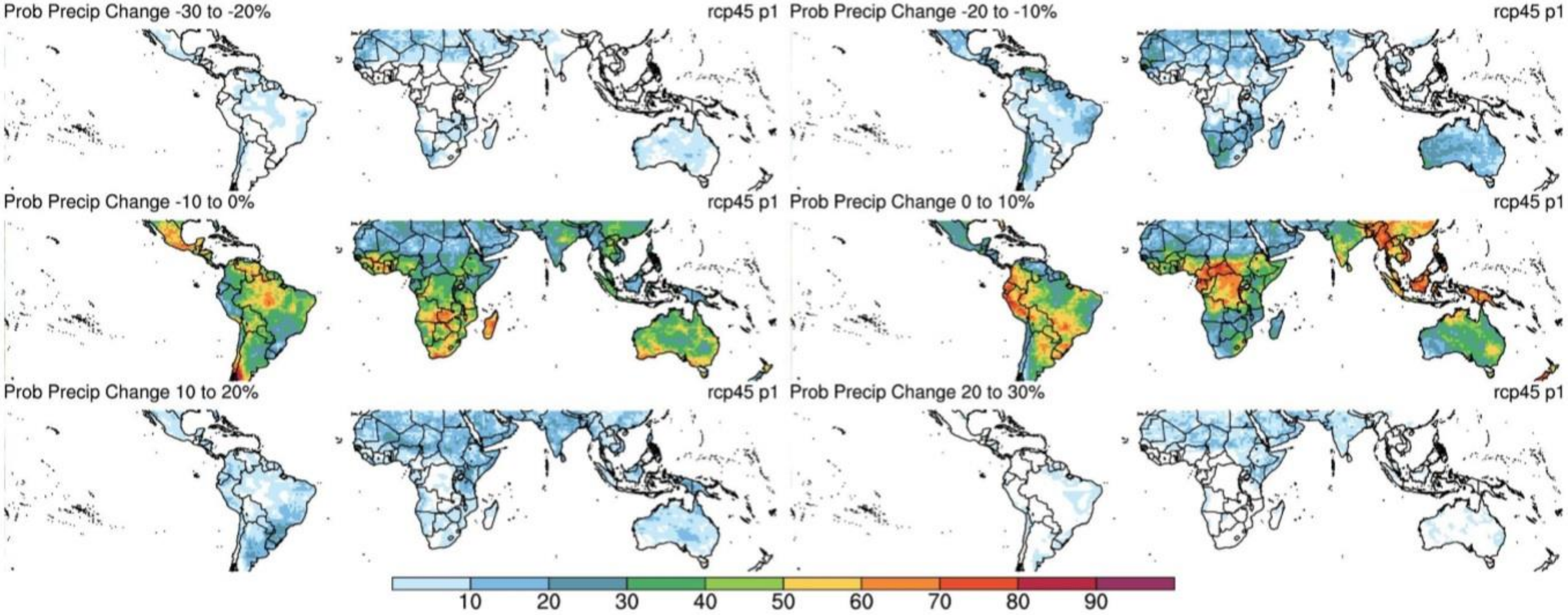


Fig 7. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP4.5 for 2050-2074

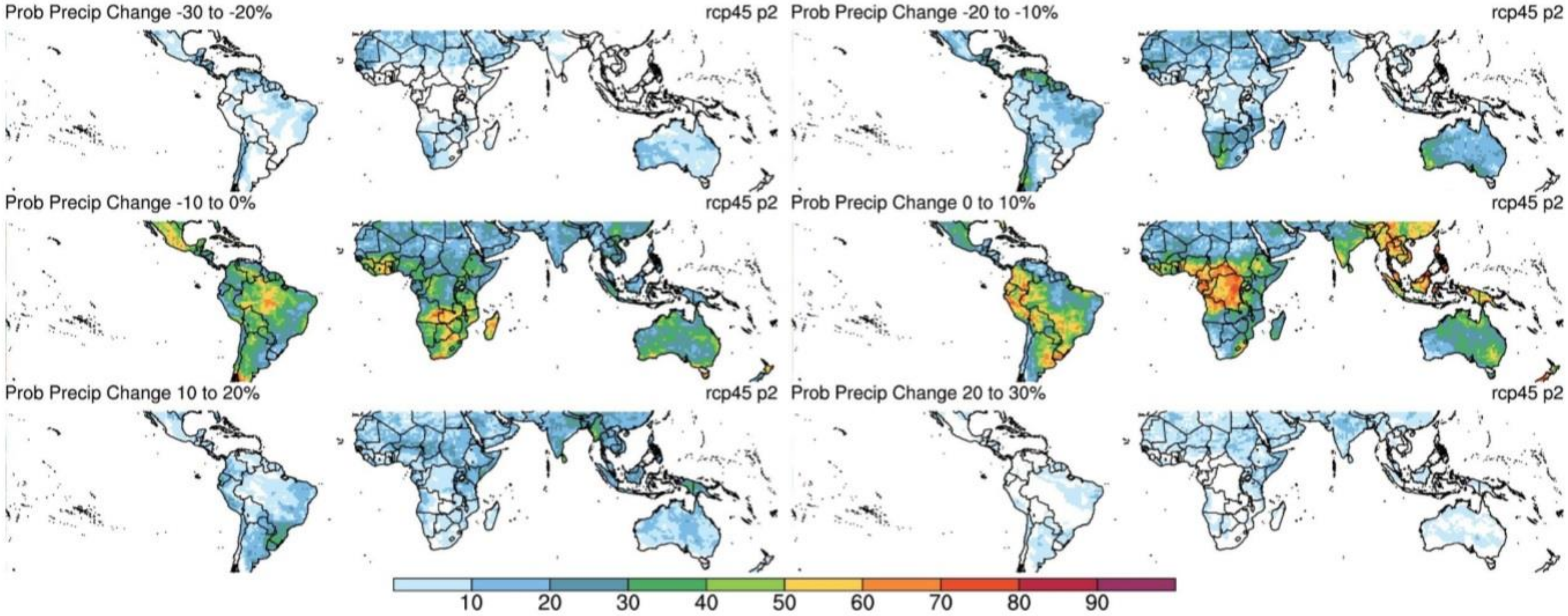


Fig 8. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP4.5 for 2075-2099

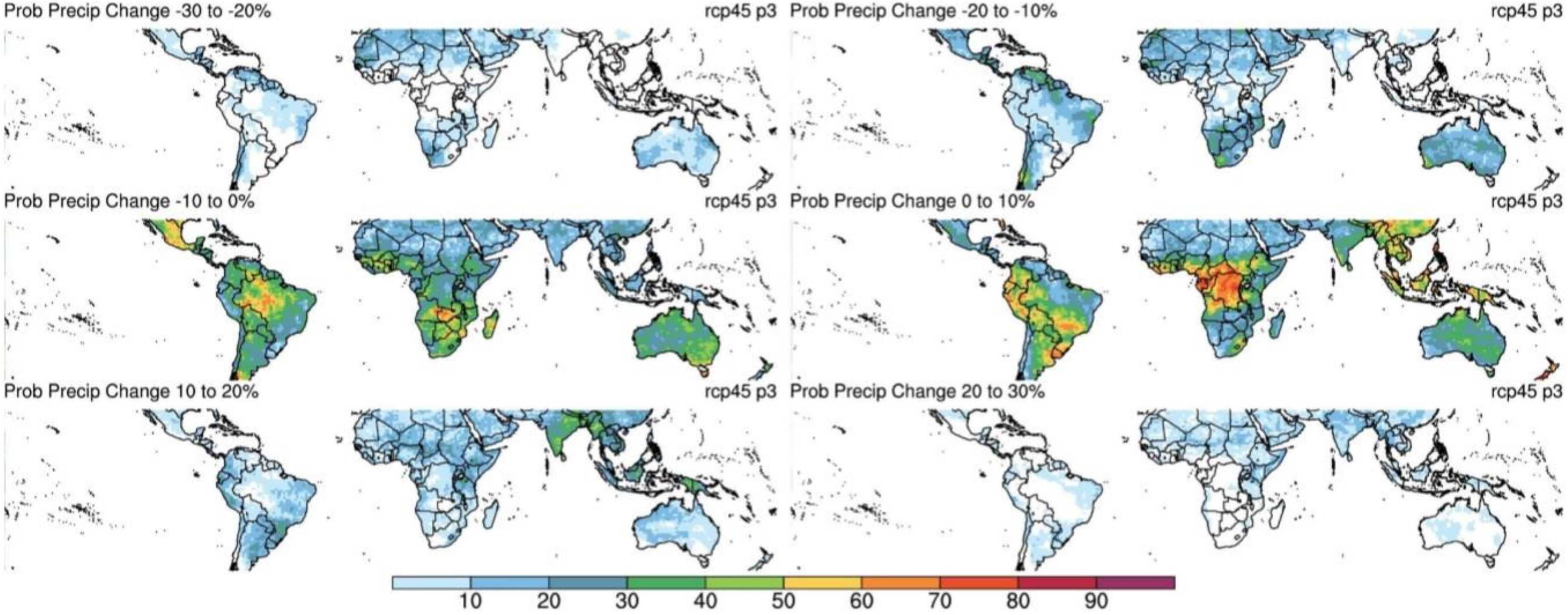


Fig 9. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP8.5 for 2025-2049

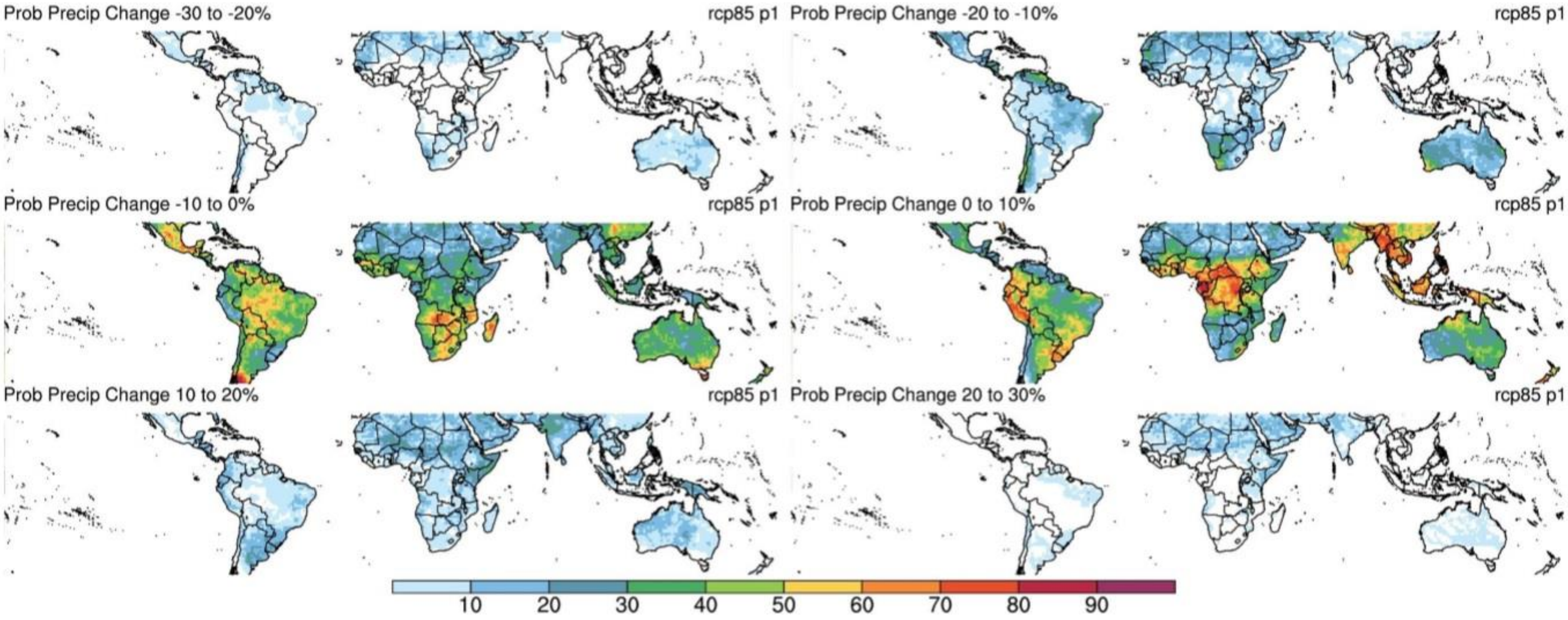


Fig 10. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP8.5 for 2050-2074

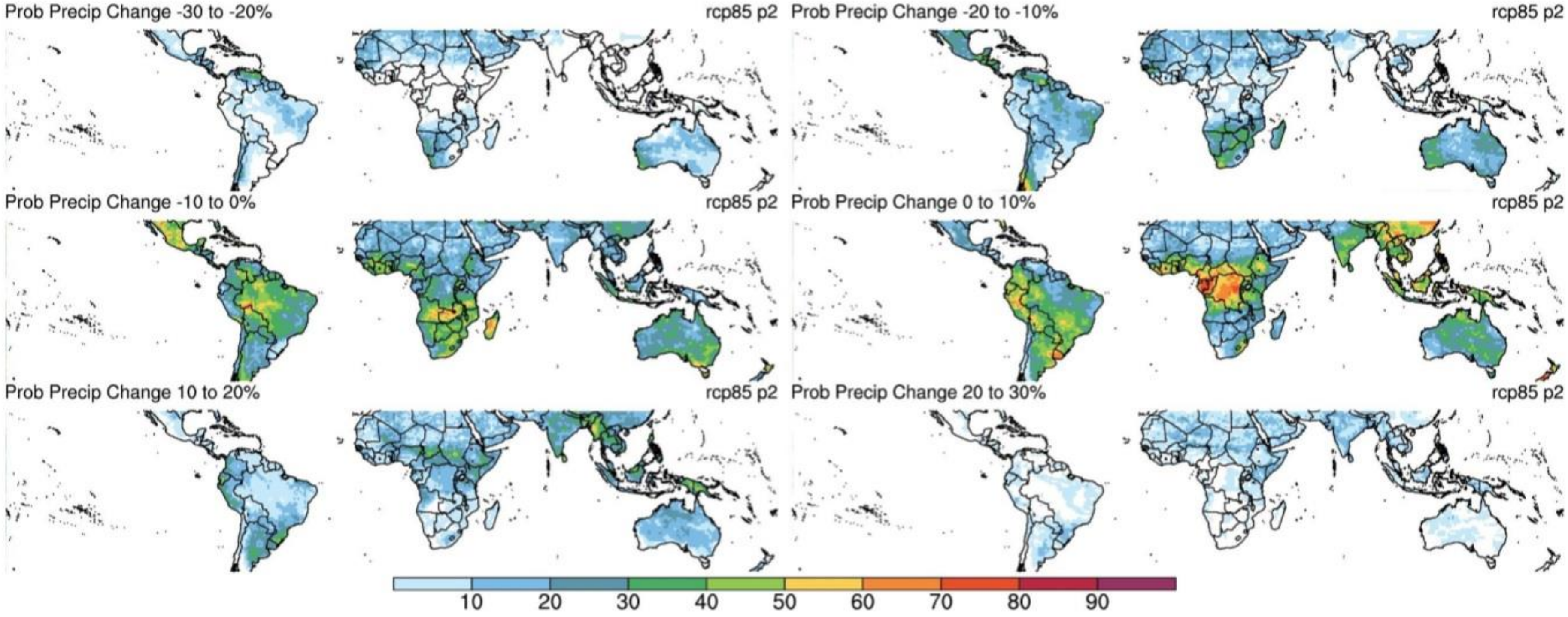


Fig 11. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099

CMIP5 Precipitation Change Probabilities (%) under RCP8.5 for 2075-2099

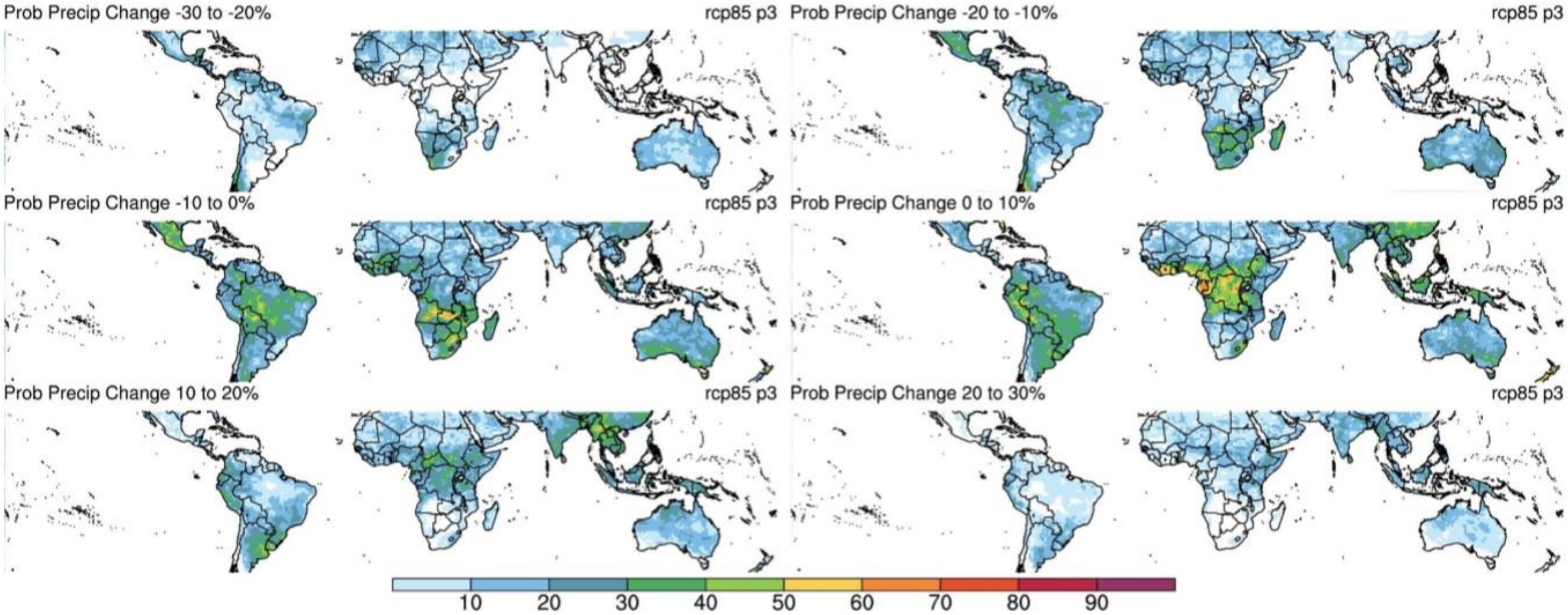


Fig 12. Probabilities of precipitation increases/decreases by intervals (-30% to 30%), estimated as the number of model projecting changes for each interval. Changes are computed as the difference between variables as projected by CMIP5 models and mean values during the historical period (1981-2005). Scenarios: RCP4.5 (moderate emission) and RCP8.5 (intense). Future projections estimated for the periods: P1: 2025-2049; P2: 2050-2074; P3: 2075-2099